Chromatic shadow compatibility and cone-excitation ratios

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Logvinenko [Perception **31**, 201 (2002)] asserts that Adelson's wall-of-blocks illusion [Science **262**, 2042 (1993)], where identical gray-cube surface tops appear to differ in brightness, arises when the surfaces surrounding the cube tops are shadow compatible, creating a concomitant illusion of transparency. We replicated Logvinenko's main findings in the chromatic domain across three experiments in which observers match cube tops in hue, saturation, and brightness. A second set of stimuli adjusted cone-excitation ratios across the apparent transparency border [Proc. R. Soc. London **257**, 115 (1994)], which enhanced lightness and brightness constancy but only when the stimuli varied in both chromaticity and intensity. © 2005 Optical Society of America

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1. INTRODUCTION

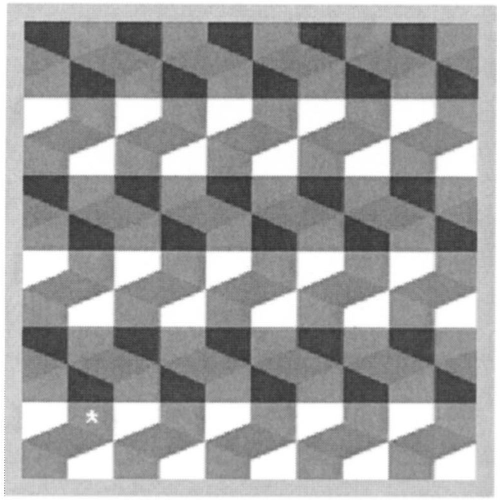
A. Achromatic Wall-of-Blocks Stimuli

Logvinenko's[1] theory of shadow compatibility is both controversial and incomplete.[2] We constructed chromatic stimuli that contain significant features of Logvinenko's[1] achromatic wall-of-blocks stimuli to explore how shadow compatibility fosters the appearance of transparency and inferred illumination. Adelson's[3] well-known tile-block pattern [Fig. 1(a)] depicts how cube tops of identical luminance appear to differ in brightness as alternating rows appear to be in shadow. The convention for differentiating "brightness" and "lightness" was first put forth by Arend and Goldstein.[4] This distinction allowed Adelson[3] to deem his stimuli a "brightness illusion," because a darker surround (or transparent filter) reduces the impression of the amount of light (i.e., perceived luminance) that reaches the eye from a surface having the same lightness (i.e., perceived reflectance) as one not in shadow. In other words, lightness constancy, by definition, states that placing a surface in shadow does not alter its lightness, only its brightness.[4]

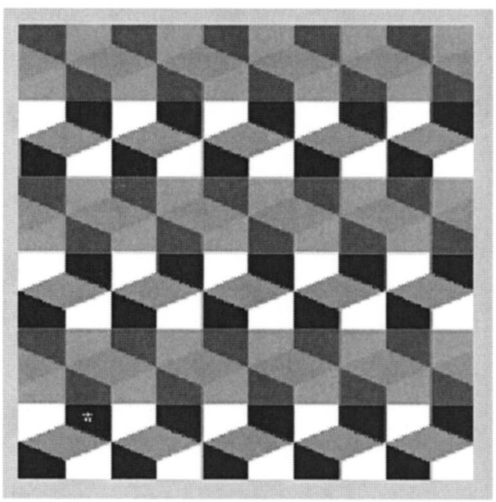
Logvinenko[1] considered Adelson's[3] phenomenon the result of shadow compatibility, a theory requiring roughly equal reflectance ratios and luminance ratios across the "shadow" borders. He calls these requisites "codirectional contrast invariance" and "equal transversal luminance ratios," respectively (e.g., see Fig. 2). Logvinenko supports his hypothesis by minimizing the brightness illusion in a shadow-incompatible condition, which introduces a single contrast reversing X-junction at a luminance edge [e.g., Fig. 2(b)]. That is, the cube tops in Fig. 1(b) appear almost equally bright by making darker the slightly shadowed side of the cubes in the unfiltered rows of Fig. 1(a) (see asterisks). However, the decrease in brightness evident in Logvinenko's[1] shadow-incompatible stimuli may be due only to increasing lower-level processes (e.g., local simultaneous contrast) created by replacing one cube top's lighter surround with a darker surround.[5]

This predicament illustrates the principal obstacle in differentiating low- and high-level explanations of virtually all simultaneous contrast paradigms. That is, they predict luminance shifts in the same direction of change.[6–8] This makes it difficult to exclude one level of processing over another or to easily determine the extent that each mechanism (low and high) may be activated. For example, multiple studies unequivocally demonstrate inconsistent results obtained with space-averaged surround stimuli, making it impossible to interpret results obtained with a space-averaged surround control for the shadow-compatible condition in a meaningful way.[9–15] A control that inverts the cube surfaces maintains the proper chromatic elements but not the spatial integrity of the structure. Given that the spatial integrity of the shadow-compatible stimulus is crucial, the best comparison is Logvinenko's shadow-incompatible stimulus,[1,2] in that it retains the requisite junctions vital to the scene by permitting a three-dimensional interpretation. However, this does not resolve the fact that the shadow-compatible condition may comprise both local and global effects.

Thus the present study attempts simply to demonstrate that observers' hue, saturation, and brightness matches covary with changes in the luminances of surrounding surfaces that are consistent with what a corre-



(a)



(b)

Fig. 1. (a) Logvinenko–Adelson[1–3] shadow-compatible wall-of-blocks illusion, (b) Logvinenko[1,2] shadow-incompatible wall-of-blocks pattern.

sponding shift in an estimate of the illuminant would predict. In other words, the question addressed is "How consistent are observers' measurements with the appearance of a real scene after addition of either a transparent filter or a shift in the illuminant?" Such consistency can be taken as evidence that shadow-compatible stimuli can evoke high-level (i.e., global) mechanisms, without excluding any role that complementary opponent processes might play. The present study seeks primarily to characterize observers' perception of chromatic versions of the illusion and secondarily to offer a parsimonious explanation of observers' responses that relies on global mechanisms (but not to the exclusion of possible contributions of other local or global mechanisms).

B. Chromatic Wall-of-Blocks Stimuli

Rayleigh[16,17] and Mie[18] scattering cause the light that reaches the earth to appear predominantly yellowish-red at dawn and dusk to blue at noon. As the location of the sun changes, shadows that also contain chromatic shifts in the illuminant may occur. As a result, these shadows often appear to contain a bluish tint.[19,20] This may also occur in a chromatic version of Logvinenko's[1] shadow-compatible illusion to the extent that it generates the appearance of different illuminant chromaticities, so that two identical chromatic cube-top surfaces can appear to differ in hue and saturation as well as in brightness.[21,22] However, the fact that humans' estimate of the illuminant typically results in only approximately 80% color constancy[21–27] implies that factors other than shadow compatibility are also operative.

Foster and Nascimento[28] explored this limitation by simulating two surface collections, called Mondrians, where the chromaticity of each surface in one Mondrian contained a fixed shift in the illuminant compared with a comparable surface in the other Mondrian. To enhance the likelihood that the two Mondrians appeared to be under different illuminants, Foster and Nascimento[28] equated comparable surfaces' cone-excitation ratios. Interestingly, observers misidentified the "corrected" Mondrians as containing the illumination change, versus those constructed with an actual shift in illumination,

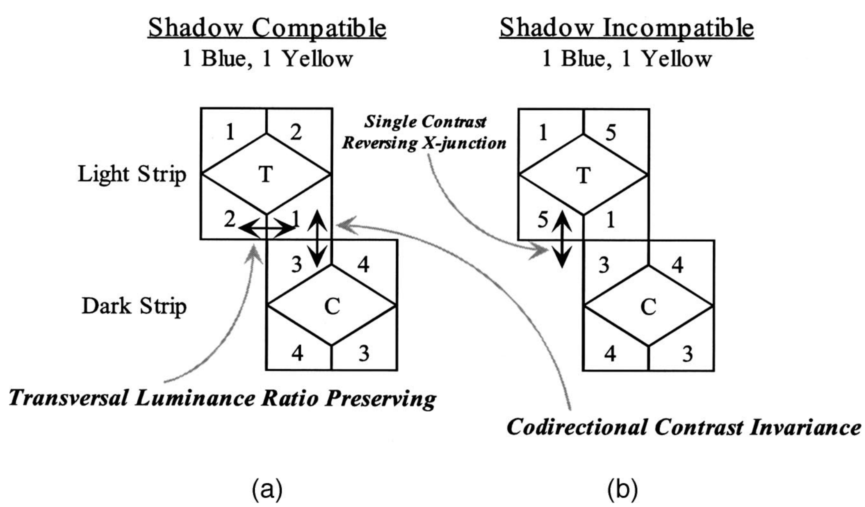


Fig. 2. Schematic of Experiment 1: intensity across, intensity up and down. (a) Shadow compatible, (b) shadow incompatible. (Intensities are displayed in Fig. 4.)

even though the former cases were highly improbable natural events.[29] These results suggest that natural shifts in illumination only approximate color constancy and that constancy can be enhanced by artificially equating cone-excitation ratios.

In recent work, Logvinenko[2] systematically varied the number of cube surfaces that reversed contrast polarity, from which he deduced that "in the natural environment, real shadows are seldom homogeneous, providing a physical reason for the deviation from codirectional contrast invariance (see Fig. 2). Hence, if the visual system strictly obeyed the codirectional contrast invariance rule, real illumination borders would often be interpreted as translucent or reflectance edges... . By using an ordinal [luminance relationship] criterion to determine shadow compatibility, the visual system reduces this type of error" (Ref. 2, p. 206). From this notion he concluded that "only ordinal information matters" (Ref. 2, p. 205). Our chromatic variations of Logvinenko's[2] achromatic shadow-compatible wall-of-blocks stimuli can test this hypothesis by using Foster and colleagues' method of equating cone-excitation ratios.[29,30] We postulate that while perceiving a shadow requires only correct ordinal contrast polarity (i.e., shadow compatibility), adjusting each cone type between adjoining surfaces to produce equal cone-excitation ratios might enhance the percept of an illumination edge. This manipulation is impossible with Logvinenko's[1] achromatic stimuli, in that it would introduce chromatic variations across the surfaces.

We constructed chromatic shadow-compatible and shadow-incompatible stimuli containing cone-excitation ratios that were either left unadjusted (i.e., with invariant within-cone-class excitation ratios) or adjusted to have average cone-excitation-ratio spacing across surfaces. We predicted that in the shadow-compatible condition observers would be more likely to estimate an illumination shift in adjusted cone-excitation-ratio conditions than in unadjusted conditions. Moreover, this effect should be most evident when the shadow-compatible border contains a shift in chromaticity as well as in luminance.

In each of three experiments, observers viewed chromatic versions of the Adelson–Logvinenko[1,3] achromatic shadow-compatible and shadow-incompatible wall-of-blocks stimuli, using adjusted and unadjusted cone-excitation ratios.[28,29] The surfaces immediately surrounding the test-cube and comparison-cube top patches varied systematically from each other in intensity [Experiment 1: Figs. 3(a) and 3(b)], intensity and chromaticity [Experiment 2: Figs. 3(c) and 3(d)], or chromaticity only [Experiment 3; Figs. 3(e) and 3(f)]. Observers adjusted the test patches (i.e., cube tops) within every other row to match in hue, saturation, and brightness either green or purple comparison patches (i.e., the remaining cube tops) within alternate rows.

2. METHOD

A. Stimuli

We generated chromatic versions of the Adelson–Logvinenko wall-of-blocks stimuli[1,3] using a Power Macintosh 7600/132 and presented them on an accurately calibrated Radius PressView 21SR 21-in. color monitor. The 832×624 pixel screen had a CIE white point of $x = 0.28$, $y = 0.29$. The scan rate was 75 Hz noninterlaced. The spectral power distribution of each phosphor was measured spectroradiometrically. Linearization of the red, green, and blue (RGB) guns used an 8-bit lookup table. The luminances set by the software were approximately constant ($\pm 3\%$) within the central region of the screen where observers were instructed to attend while making matches.

Stimuli were simulations of a gray Munsell paper (N/5) illuminated by different daylights to appear like a wall of cubes. RBG values were computed by going from Judd[31] x', y', to cone long-, medium-, and short-wavelength (LMS) space.[32,33] We normalized the sensitivities of the receptor system such that the L, M, and S cones received equal quantum catches at equal-energy white ($x = y = 0.33$).[34] The LMS-cone receptor inputs were then used as is (i.e., "unadjusted," with cone input as a function of surface intensity $R^2 = 1.0$), or we "adjusted" the LMS-cone receptor inputs by determining the average difference in excitation in each cone type between adjacent surfaces and then set the cone-receptor inputs between adjacent surfaces to this average difference using a best linear fit. This reduced cone input as a function of surface intensity from $R^2 = 1.0$ to $R^2 = 0.993$. These values were then converted to Macleod–Boyton (l, s, Y) space.[35] We scaled s to 1.0 for equal-energy white.

Each diamond-shaped cube top was $2.5° \times 5°$ and either a simulation of a green Munsell (5GY7/10) or a purple Munsell (5P7/6) paper under a 5300° K (i.e., "neither bluish or yellowish" appearing illuminant).[36] Experiment 1 simulated the gray cube surfaces to be under either a bluish (20,000° K) or a yellowish (2856° K) illuminant that varied only the intensity of the patches within and between adjacent horizontal strips [Fig. 2 is a schematic of the shadow-compatible and shadow-incompatible surface luminance relations, and Figs. 3(a) and 3(b) approximate the bluish illumination conditions]. To determine the intensity of each surface required equating adjacent surface luminance ratios. B1–B5 represents the intensity of the bluish surfaces and Y1–Y5 represents the intensity of the yellowish surfaces (where 1–5 refer to 60, 42, 24, 16.8, and 9.6 cd/m^2, respectively; see Fig. 4).

Figure 2(a) is a schematic of the surface luminance relations used in the first experiment's blue shadow-compatible condition. It has invariant B1/B3 and B2/B4 ratios (i.e., equal codirectional contrast ratios of 2.5 across the luminance border) and invariant B1/B2 and B3/B4 ratios (i.e., equal transversal luminance ratios of 1.43 within each horizontal strip). The same ratios occur with the yellow shadow-compatible intensities (Y1–Y4; not shown). Logvinenko[1] claimed that selecting the luminances of abutting surfaces to make their edge ratios invariant (i.e., shadow compatible) would make the display appear to contain strips that alternate in their level of illumination [e.g., Figs. 2(a) and 3(a)]. Replacing B2 with B5 creates the blue shadow-incompatible stimulus. While B1/B3 still equals 2.5, B5/B4 now equals 0.23, and while B3/B4 still equals 1.43, B1/B5 now equals 6.25 [see Fig. 2(b)]. This manipulation violates codirectional con-

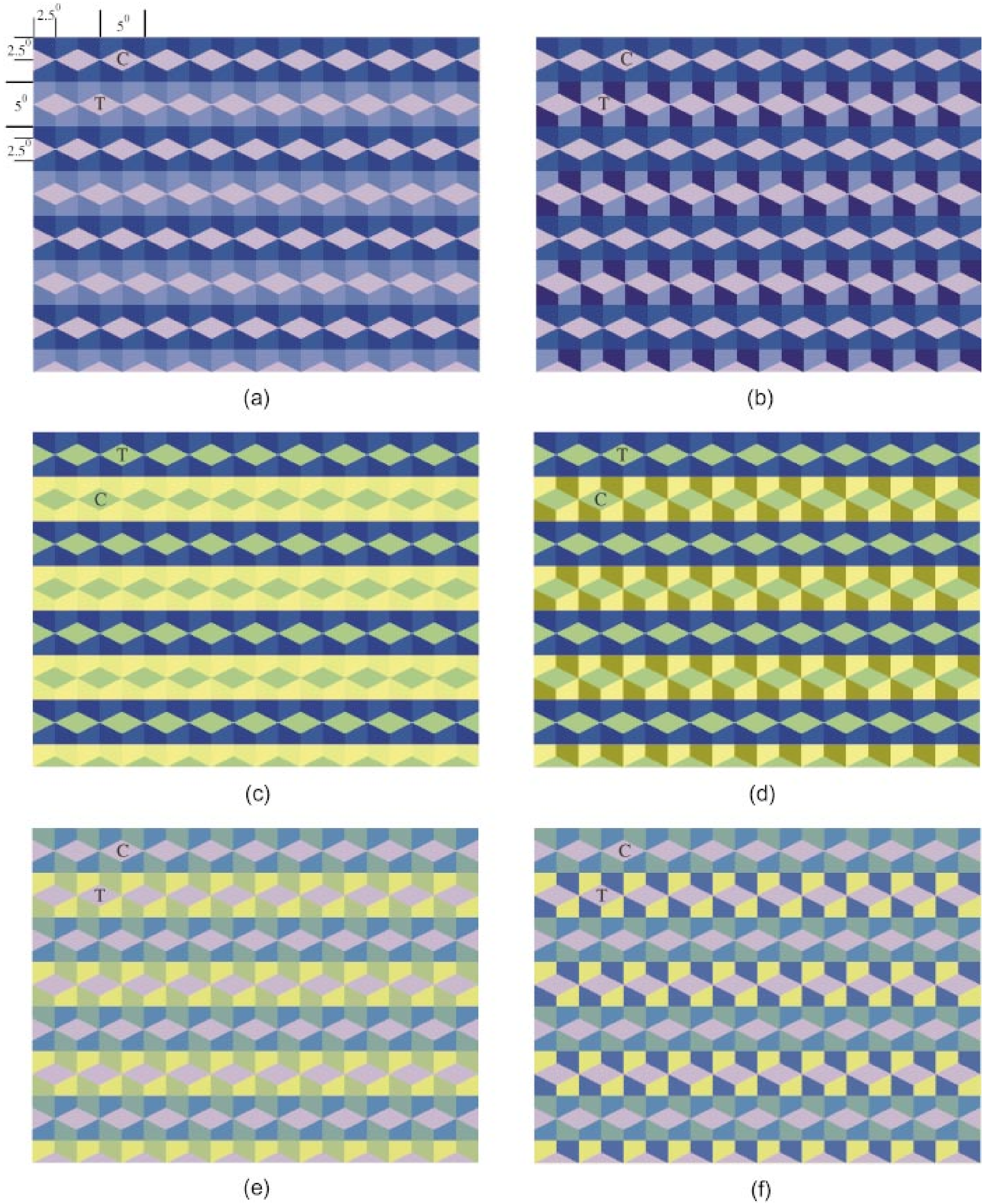


Fig. 3. Caption on facing page.

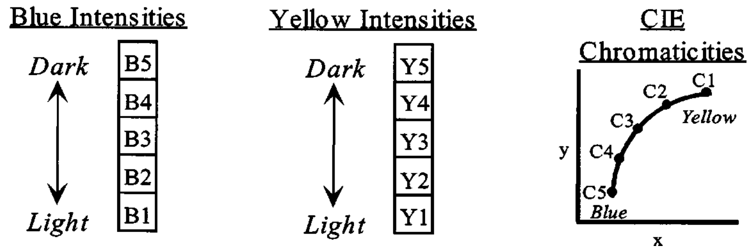


Fig. 4. Schematic of intensities and chromaticities displayed in Figs. 4, 5, and 7.

trast invariance, creating unequal luminance ratios across and along the apparent illumination borders [Fig. 3(b)]. Experiment 1's stimuli [Figs. 3(a) and 3(b)] are therefore isochromatic versions of Logvinenko's achromatic stimuli.[1] The test patches (T) consisted of rows of cube top surfaces being adjacent to the lighter surrounds, and the comparison patches (C) consisted of the rows of cube-top surfaces being adjacent to the darker surrounds.

We created the stimuli of Experiment 2 by interdigitating by row the blue and yellow surrounds used in Experiment l's stimuli [Fig. 5 is a schematic of the shadow-compatible and shadow-incompatible surface luminance relations, and Figs. 3(c) and 3(d) approximate these configurations]. This manipulation introduced a chromatic difference across row borders to accompany the within-row and across-row border intensity differences. This meant that Experiment 2's stimuli contained both chromatic and intensity ratios along Y1/B3 and Y2/B4, as well as intensity ratios along Y1/Y2 and B3/B4. These ratios across and along a row were equal in the shadow-compatible condition [see Figs. 3(c) and 5(a)] and were made unequal (i.e., shadow incompatible) by replacing the Y2 patches with Y5 patches [Figs. 3(d) and 5(b)]. Thus the shadow-compatible stimuli appeared to consist of alternating light-yellow and dark-blue strips [Fig. 3(c), where yellow surfaces are represented by Y1 and Y2 and blue surfaces are represented by B3 and B4]. According to Logvinenko's[1] achromatic shadow-incompatible stimulus (e.g., his Fig. 3) the strips in this chromatic version [Fig. 3(d)] should appear translucent without preserving brightness shifts.

In Experiment 3, we systematically varied only the stimuli's chromaticity. Each surface was a simulated gray Munsell paper (N/5) that could be under one of five different illuminants spaced roughly equidistant along the blackbody locus (see Fig. 6 dots-within-circles, and CIE (C1–C5) plot in Fig. 4: 2856° K (Illum. A), 4000°, 5300°, 7500°, and 20,000° K). This resulted in each cube surface appearing to have a different source of illumination [Figs. 3(e) and 3(f)]. The choice to use points along

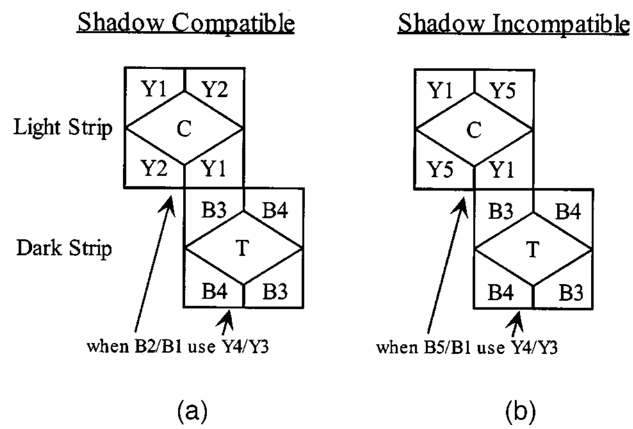


Fig. 5. Schematic of Experiment 2: intensity across, chromaticity up and down. (a) Shadow compatible, (b) shadow incompatible. (Intensities and chromaticities are displayed in Fig. 4.)

the blackbody locus as the illuminants was guided by the assumption that the visual system is particularly sensitive to this direction in color space when determining differences in illumination. In essence, we altered each L, M, and S value first for the 4000° K illuminated surface and then the 2856° K illuminated surface (likewise, first for the 7500° K and then the 20,000° K values) while holding the L, M, and S receptor input values constant for the 5300° K illuminated surface. This resulted in constant L, M, and S ratios between each surface and its adjacent neighbor. This is comparable to what we did in Experiment 1, where we adjusted the L, M, and S ratio between each surface and its adjacent neighbor. The two extreme temperatures were identical to the yellowish and bluish illuminants used in Experiments 1 and 2. Comparable to the intensity ratios in Experiment 1, the chromaticity ratios along and across the borders of Experiment 3's shadow-compatible stimuli were invariant. That is, C1/C2 = C3/C4, etc. The shadow-incompatible condition replaced one surface's illuminant with a more extreme, opposite illuminant.

Fig. 3. On facing page. (Images are significantly more saturated and only approximate the CRT displays.) Experiment 1, intensity variation: (a) shadow-compatible blue isochromatic stimuli (i.e., the light-blue strip is composed of B1 and B5, and the dark-blue strip is composed of B3-B4), (b) shadow-incompatible blue isochromatic stimuli (i.e., the light-blue strip is composed of B1 and B2, and the dark-blue strip remains composed of B3-B4). Test patches (T) are within the lighter surrounds, and comparison-patches (C) are within the darker surrounds. Experiment 2, chromatic and intensity variation: (c) shadow-compatible stimuli (i.e., the light-yellow strip is composed of Y1 and Y2, and the dark-blue strip remains composed of B3-B4), (d) shadow-incompatible stimuli (i.e., the yellow strip is composed of Y1 and Y5, and the blue strip is composed of B3-B4). Test patches are within the darker surrounds and comparison patches are within the lighter surrounds. Experiment 3, chromatic variation in the yellowish range: (e) shadow-compatible stimuli [i.e., the yellowish strip is composed of C1 and C2 (or C3-C2), and the bluish strip is composed of C3-C4 (or C5-C4)], (f) shadow-incompatible stimuli [i.e., the yellowish strip is composed of C1 and C5 (or C3-C2), and the bluish strip is composed of C3-C4 (or C5-C1)]. Test patches are in the surrounds that vary across compatibility conditions, and comparison patches are in the surrounds that are invariant across compatibility conditions.

For example, Fig. 7(a) shows the shadow-compatible stimuli with the "more-yellowish" range of chromaticities C1–C4 [Fig. 3(e)] and the "more-bluish" range of chromaticities C2–C5 (not shown in Fig. 3). The shadow-incompatible conditions [Fig. 7(b)] simply switched C2 to C5 [Fig. 3(f)] and C4 to C1 (not shown in Fig. 3), respectively. Our intent was for this purely chromatic stimulus structure to be consistent with Logvinenko's achromatic stimulus structure.[1] Note that the surrounds immediately adjacent to the rows of test patches share the same strip and range of chromaticities when shadow compatible. For example, the test patches (T) in the shadow-compatible yellowish range condition are adjacent to the more-yellowish surrounds. Consequently, the comparison patches (C) are adjacent to surrounds that remain invariant across shadow-compatible and shadow-incompatible conditions.

Caveats regarding Experiment 3's stimuli include the fact that we did not alter the surface luminances to account for the specific spectral sensitivities of each observer. In other words, we made no attempt to make the resulting regions isoluminant by using techniques such as heterochromatic flicker photometry. Making each observer's stimuli isoluminant would have made each of their cone ratios different, resulting in an analysis that would have been beyond the scope of the current project. Second, Experiment 3's stimuli may be considered less ecologically realizable than the stimuli used in the first and second experiments. Our only intent in constructing Experiment 3's stimuli was to use chromaticity points in a manner comparable to Logvinenko's[1] use of luminance steps. We make no assumptions regarding what the visual system might "infer" from such a collection of chromatic relationships but rather seek simply to determine if their resulting arrangements are consistent with an interpretation of multiple sources of illumination. Finally, these particular stimulus conditions may not produce the maximal effect that might be possible using other luminance or chromatic relations.

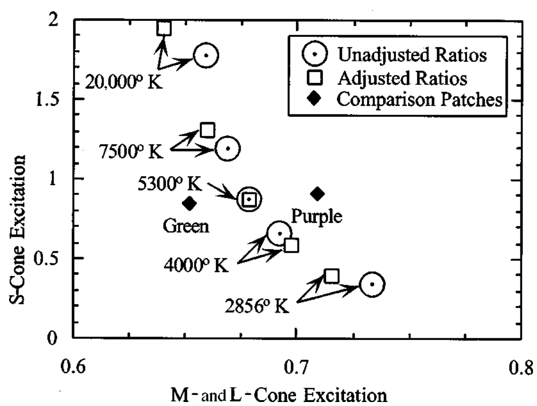


Fig. 6. Stimulus chromaticities. Unadjusted (dots-within-circles) and adjusted (squares) cone-excitation ratios, plotted in MacLeod–Boynton (LMS) color space.[35] The extreme temperatures (i.e., 2856° K and 20,000° K) were the yellowish and bluish surrounds used in Experiments 1 and 2. The complete range composed the surrounds used in Experiments 3. Also plotted are the green Munsell (5GY7/10) and purple Munsell (5P7/6) comparison papers under 5300° K illuminant.

Each experiment also contained a fourth condition that manipulated cone-excitation ratios. One set of shadow-compatible and shadow-incompatible conditions used unadjusted cone-excitation ratios, which would result from placing part of a gray Munsell paper under a given illuminant (i.e., where the ratio of cone-photoreceptor excitations produced by light across the illumination edge was invariant). A second set of shadow-compatible and shadow-incompatible conditions used adjusted cone-excitation ratios (i.e., where the ratio of cone-photoreceptor excitations was first adjusted across surfaces to be of equal spacing, while the best possible linear fit was maximized). While the adjusted cone excitations reduce R^2 from 1.0 to 0.993, such a reduction is permissible because the critical issue is not having perfectly linear cone-excitation ratios (which shadow compatibility ensures) but rather producing the best linear fit after adjusting the cone-excitation spacing between different adjacent surfaces (which shadow compatibility does not ensure). This adjustment is especially significant because it creates a condition that cannot occur with achromatic stimuli. Only with chromatic displays can there be an enhancement in inferring an illumination border (as predicted by Foster and Nascimento[28]) as each cone-type excitation deviates away from an $R^2 = 1$ regression line.

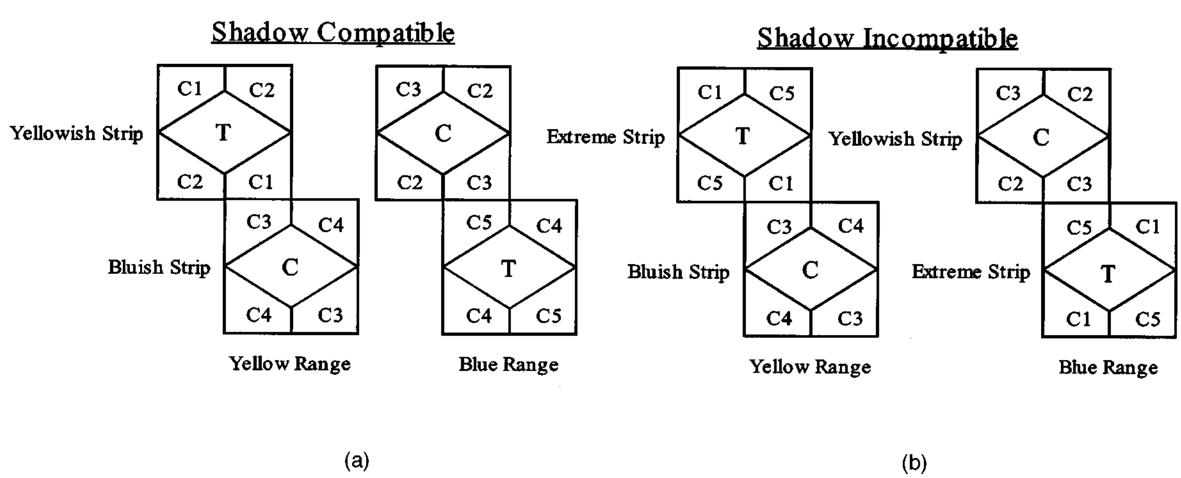


Fig. 7. Schematic of Experiment 3: chromaticity across, chromaticity up and down. (a) Shadow compatible, (b) shadow incompatible. (Chromaticities are displayed in Fig. 4).

Table 1. Experiment 1: Test-Patch Difference Score Means as a Function of Shadow Compatibility, Cone-Excitation Ratios, Stimulus Color Scheme, and Test-Patch Color

	Shadow Compatible				Shadow Incompatible			
	Adjusted		Unadjusted		Adjusted		Unadjusted	
Test Patch	Blue	Yellow	Blue	Yellow	Blue	Yellow	Blue	Yellow
s values								
Green	−0.0011	0.0774	0.0129	0.1030	−0.0265	0.0542	−0.0264	0.0489
Purple	0.0397	0.1210	0.0443	0.1190	0.0264	0.0954	0.0129	0.0696
Y values								
Green	1.863	1.632	1.771	1.215	−8.564	−7.093	−8.011	−6.545
Purple	6.378	6.895	7.264	7.947	−1.880	−1.598	−0.622	−0.928

Figure 6 shows the cube surfaces' unadjusted (dots within circles) and adjusted (squares) cone-excitation ratio chromaticities in MacLeod–Boynton space.[35] It also shows the chromaticities of the green ($l = 0.6389$, $s = 0.8410$, and $Y = 24\,\mathrm{cd/m^2}$) and purple ($l = 0.6821$, $s = 0.9009$, and $Y = 24\,\mathrm{cd/m^2}$) comparison patches (diamonds) located to the left and right, respectively, of the blackbody locus.

B. Procedure

Observers ran each experiment in a single session and could run up to two sessions per day. The chin rest they used was located 45 cm from the monitor in an otherwise dark room. Each session began with 3 min of dark adaptation followed by 3 min of light adaptation to the average intensity and chromaticity of the stimulus set. When each stimulus appeared on the screen, the rows of test patches initially appeared black. Observers used a joystick to adjust simultaneously all the rows of test patches to match the rows of comparison patches in hue, saturation, and brightness. We told them specifically to make the rows appear identical and to attend to the center of the screen when making adjustments. Pushing one button and moving the joystick back and forth changed the intensity of the test-patch rows, and pushing a second button and moving the joystick around in two-dimensional space varied hue and saturation analogous to moving within a color circle. Once satisfied with a match, observers pressed a third button to record the setting. Following 10 s of light adaptation, they automatically received the next stimulus. We presented sessions randomly, and stimuli conditions (i.e., shadow compatibility, cone-excitation ratio, comparison patch, and surround) within a session pseudorandomly without replacement. In a single experimental session, each of 12 observers judged 3 separate blocks with each condition occurring once per block. Debriefing occurred after the third session.

The method of adjustment can alter slightly the color relations among the individual elements, which can potentially differentially activate lower and higher mechanisms. However, many studies investigating the validity of asymmetric color matching[37] concur that this method is a justifiable procedure.

C. Results

The computer converted the comparison-patch and the test-patch RGB settings into MacLeod–Boynton l, s, and Y coordinates,[35] and calculated the results for all three experiments as l, s, and Y coordinates difference scores. That is, it subtracted the l, s, and Y value of a given comparison patch from an observer's l, s, and Y test-patch setting. The l value (x axis) indicates the relative proportion of L- and M-cone excitation, the s-value (y axis) corresponds to the amount of S-cone excitation, and the Y-value (z axis) corresponds to intensity in $\mathrm{cd/m^2}$ (Fig. 6). A positive or negative difference score indicates that the test patch was set higher or lower, respectively, for a particular coordinate than its comparison-patch value.

In all three experiments, the dependent variables were each of the three MacLeod–Boynton space coordinates (i.e., l, s, and Y),[35] and the four within-subject independent variables were (1) shadow compatibility versus shadow incompatibility, (2) adjusted versus unadjusted cone-excitation ratios, (3) blue versus yellow surrounds, and (4) green versus purple comparison patches. This resulted in a four-way ($2 \times 2 \times 2 \times 2$) multivariate analysis of variance (MANOVA). Having 12 observers judge each condition 3 times resulted in a mean difference score ($n = 36$) for each condition (Table 1, Experiment 1; Table 2, Experiment 2; Table 3, Experiment 3). All statistical tests were done on difference scores.

D. Observers

Twelve Wake Forest University introductory psychology undergraduates (nine females) participated in all three experiments for course credit. All had normal or corrected visual acuity and tested color normal via pseudoisochromatic plates.[38]

3. EXPERIMENT 1

A. Results

In Experiment 1, the rows of test patches were adjacent to the lighter surrounds, and the rows of comparison patches were adjacent to the darker surrounds [e.g., Figs. 3(a) and 3(b)]. To match the brightness of the comparison patches, observers set the intensity (Y) of the green test patches 38% higher and the intensity of the purple patches 35% higher in the shadow-compatible conditions (solid circles) compared with the shadow-incompatible conditions (squares) (see Fig. 8). This univariate main

Table 2. Experiment 2: Test-Patch Difference Score Means as a Function of Shadow Compatibility, Cone-Excitation Ratios, Stimulus Color Scheme, and Test-Patch Color

	Shadow Compatible				Shadow Incompatible			
	Adjusted		Unadjusted		Adjusted		Unadjusted	
Test Patch	Blue	Yellow	Blue	Yellow	Blue	Yellow	Blue	Yellow
s values								
Green	0.203	−0.234	0.238	−0.264	0.259	−0.250	0.280	−0.262
Purple	0.258	−0.126	0.282	−0.200	0.320	−0.169	0.394	−0.178
Y values								
Green	−10.310	−13.202	−11.127	−14.975	−7.649	−9.005	−8.188	−10.129
Purple	−3.684	−5.320	−4.691	−7.024	−0.484	−0.352	−2.238	−1.164

Table 3. Experiment 3: Test-Patch Difference Score Means as a Function of Shadow Compatibility, Cone-Excitation Ratios, Stimulus Color Scheme, and Test-Patch Color

	Shadow Compatible				Shadow Incompatible			
	Adjusted		Unadjusted		Adjusted		Unadjusted	
Test Patch	Blue	Yellow	Blue	Yellow	Blue	Yellow	Blue	Yellow
s values								
Green	−0.121	−0.068	−0.114	−0.013	−0.029	−0.030	−0.026	−0.014
Purple	−0.016	−0.011	−0.048	0.027	0.059	0.017	0.049	0.044
Y values								
Green	−5.273	−4.744	−5.289	−7.056	−5.378	−4.926	−4.750	−5.284
Purple	0.734	1.903	0.968	1.062	0.834	0.989	1.028	1.821

effect was statistically significant [$F(1, 176) = 451.865$, $p < 0.001$; Fig. 8(a) and Table 1]. This pattern-of-difference score suggests that for shadow-compatible stimuli, the test patches within the lighter surround appeared dimmer than the comparison patches, or the comparison patches within the darker surround appeared brighter than the test patches, or both.

For the S-cone-excitation difference scores, there was a statistically significant univariate main effect of shadow compatibility [$F(1, 176) = 9.536$, $p < 0.002$; Table 1]. Observers set the test patches' s values further from the comparison patches (i.e., by 3.9% for the green patch and 3.1% for the purple patch) in the shadow-compatible condition (solid circles) compared with the shadow-incompatible condition (squares) [Fig. 8(b) and Table 1]. This result implies that shifting from the shadow-incompatible to the shadow-compatible condition made the test patches appear more yellow or the comparison patches appear more blue, or both.

Closer examination of the univariate main effect revealed the s-value difference value of 0.0660 for the purple test patches was ~2.2 times that of the green test-patch value of 0.0303 [$F(1, 176) = 11.312$, $p < 0.001$; Table 1], and regardless of test-patch color, the s-value difference value for yellow stimuli (0.0861) was ~8.4 times that for blue stimuli (0.0103) [$F(1, 176) = 51.121$, $p < 0.001$; Table 1]. A MANOVA revealed that none of the main effects we presented were statistically significant for l difference scores (i.e., relative L- and M-cone-excitation) [$F(3, 174) = 0.333, p = 0.565$].

B. Discussion

If a neutral density filter (e.g., a shadow) covered the region surrounding the comparison patches without changing their actual luminance, the comparison patches would appear brighter, or the test patches would appear dimmer, or both. This is exactly what we found in the shadow-compatible condition [Figs. 3(a) and 8(a)]. Recall that a shadow interpretation results in a brightness, not a lightness, shift. This implies attributing a constant proportion of the luminance that reaches the eye to surface reflectance (i.e., lightness) and a varying amount to a shift in illumination (i.e., brightness due to a shadow or filter).

The results shown in Fig. 8(a) suggest further that observers do distinguish between lightness and brightness. For example, observers set the Y value in the shadow-incompatible condition quite differently depending upon the test-patch color. The large luminance changes obtained with green but not purple cube tops may be due primarily to differences in lower-level local contrast mechanisms. Making these stimuli shadow compatible produced an almost fixed gain independent of test-patch color, which suggests that shadow compatibility does not release the visual system from lower-level processes but simply augments differences in inferred illumination, resulting in consistent shifts in brightness. These data provide an excellent example of how lower- and higher-level mechanisms work in tandem.

Interestingly, our isochromatic stimuli elicited a greater s-value difference value in the shadow-compatible condition than in the shadow-incompatible condition [Fig. 8(b)]. This provides additional, albeit indirect, evidence that shadow compatibility enhances the appearance of a shadow over the comparison patches. For example, in natural scenes real reductions in illumination often make shadows appear to contain a bluish tint.[19] We suggest that this ecological event creates the propensity for the visual system to also infer a bluish tint whenever a shadow interpretation is evoked.[20] From this idea follows the suggestion that for cases in which a shadow interpretation is consistent but the characteristic bluish tint is absent (e.g., our shadow-compatible case), observers respond by correcting for the absence of the bluish tint.[39] Put differently, if there were a bluish-appearing shadow, then the cube tops that it covered would appear too yellow. Consequently, observers would, and did, increase the S-cone excitation of the cube tops (i.e., they made these regions appear more blue to compensate) in the shadow-compatible condition.

To check the reliability of this novel claim, we had five independent observers set the test diamonds one just-noticeable difference away from the comparison diamonds (i.e., $s = 0.9009$) on an otherwise black surround. This difference was always $<2\%$ ($n = 20$ trials/observer). These measurements are roughly equivalent to those reported by Golz and MacLeod.[40] Moreover, equal variance around these settings also implies that observers did not err significantly more in the positive S-cone-excitation direction than in the negative S-cone-excitation direction as reported by Krauskopf and Gegenfurtner[41] (who obtained just-noticeable-difference thresholds using a four-alternative-forced-choice of $b = 0.0012$). Thus the $>3\%$ magnitude of our S-cone shifts corroborate the suggestion that our shadow-compatible condition could have evoked a shadow interpretation.

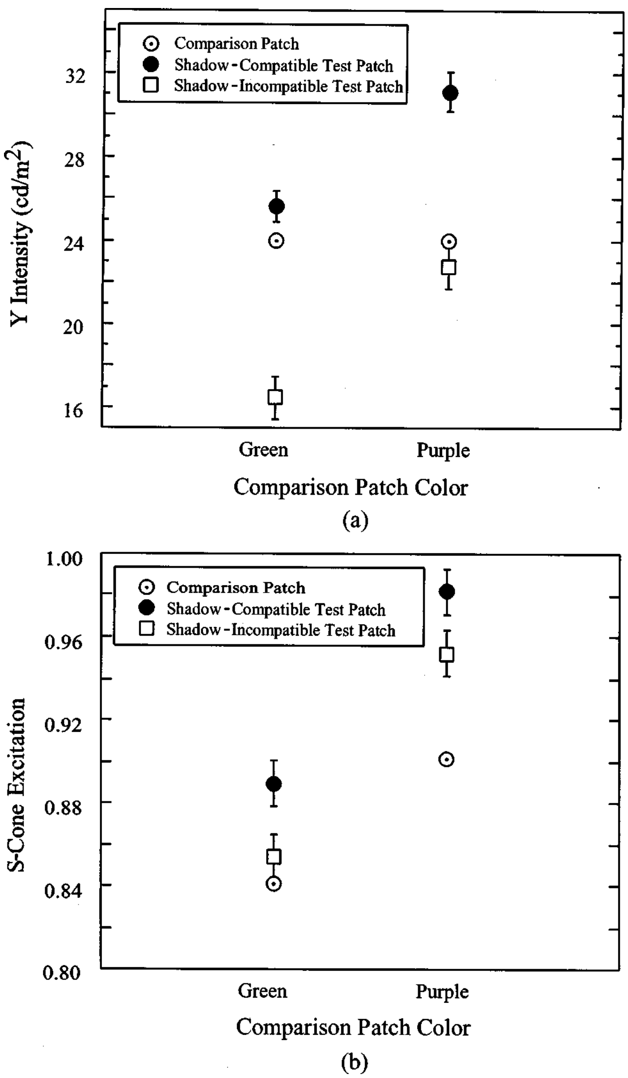


Fig. 8. Experiment 1 main effect [and standard error of the mean (SEM)] of shadow compatibility for (a) Y-value scores (cd/m^2) and (b) s-value scores.

Comparing the results between isoluminant yellow and isoluminant blue stimuli provide additional support for this proposition. Regardless of test-patch color, observers added more than eight times as much short-wavelength light to test patches in the isochromatic yellow as in the isochromatic blue stimulus configuration. This result is interesting because the comparison regions of both stimulus configurations appear darker in the shadow-compatible than in the shadow-incompatible condition. We suggest that in the blue stimulus configuration, the darker comparison region results in S-cone excitation across the entire scene, which prompts the observer to attribute any bluish tint inferred by shadow compatibility to the surface properties of the scene. Thus to obtain a brightness match, observers need not respond to this surface property interpretation by making comparable changes to the S-cone excitation of the test patches. Were complete adaptation possible, such an image would appear to contain blue surfaces under neutral illumination. Conversely, we suggest that the yellow stimulus configuration caused observers to attribute any bluish tint inferred by shadow compatibility to the shadow, that is, the illumination properties of the scene. In this case, obtaining a brightness match required that observers respond to this shadow interpretation by significantly increasing the short-wavelength light of the test patches.

Obtaining a shift in S-cone excitation in our isochromatic shadow-compatible condition is consistent with Logvinenko's[1] high-level-vision interpretation to the extent that a shadow may also appear to contain a bluish tint.[19,20] We do not know of any comparable low-level-vision mechanisms (e.g., those involving local induction) or midlevel-vision mechanisms (e.g., those that evoke junctions) to account for such findings. Though mechanisms at multiple levels are also likely to be operative when these stimuli are viewed, shadow compatibility provides a parsimonious explanation for the shift in S-cone excitation. Moreover, these results agree with and extend to the chromatic domain Logvinenko's high-level-vision achromatic hypothesis.[1]

4. EXPERIMENT 2

A. Results

Recall that unlike in Experiment 1, the rows of test patches in Experiment 2 were always adjacent to the darker surrounds, which could be either yellow or blue [e.g., Figs. 3(c) and 3(d)]. A univariate ANOVA revealed

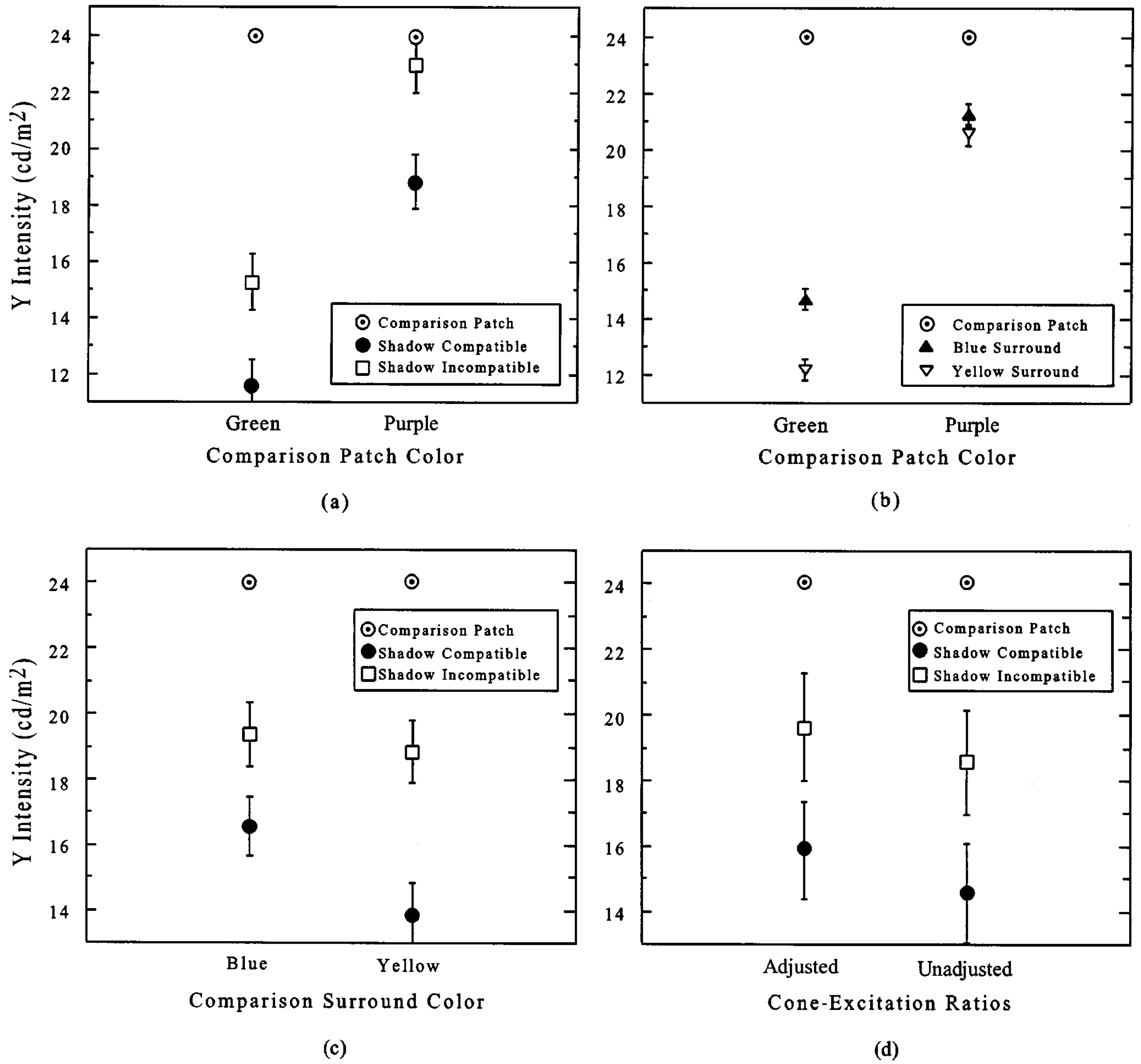


Fig. 9. Experiment 2 main effect (and SEM) of shadow-compatibility Y-value scores (cd/m^2) as a function of (a) comparison patches, (b) test surrounds, (c) test and comparison surrounds, and (d) cone-excitation ratios.

that to match the brightness of the comparison patches, observers decreased the intensity (Y) of the green test patches 15% more and of the purple patches 17% more in the shadow-compatible condition (solid circles) than in the shadow-incompatible condition (squares) [$F(1, 176) = 104.731$, $p < 0.001$; Fig. 9(a) and Table 2]. As in Experiment 1, this result implies that either the shadow-compatible condition made the test patches within their darker surround appear brighter, or the comparison patches within their lighter surround appeared dimmer, or both.

While the direction of the difference in s-value setting for the shadow-compatible versus the shadow-incompatible condition was the same as in Experiment 1, a slight reduction in effect size for the green patch made it statistically insignificant in Experiment 2 (i.e., $p = 0.068$).

As expected, on blue surrounds observers added blue to the test patches (i.e., s-value difference score = 0.279), presumably because they appeared too yellow, and on yellow surrounds they added yellow to the test patches {i.e., s-value difference value = -0.210) presumably because they appeared too blue [$F(1, 176) = 896.385$, $p < 0.001$; Table 2]}.

Observers set the test patches to lower Y values, presumably because they appeared brighter, on dark yellow compared than on dark blue surrounds [$F(1, 176) = 5.723$, $p < 0.018$; Fig. 9(b); Table 2]. As in Experiment 1, the green test patches on the dark yellow surround were set dimmest. Likewise, Fig. 9(c) shows that observers set the test patches dimmer in the shadow-compatible condition (solid circles) than in the shadow-incompatible condition (squares) and that this univariate effect was stronger for yellow surrounds than for blue surrounds [$F(1, 176) = 8.032, p < 0.005$].

Figure 9(d) shows that observers decreased the test patches' Y value within their dark surround more when viewing unadjusted cone-excitation ratios (31%, on average) than when viewing adjusted cone-excitation ratios (26%, on average) [$F(1, 176) = 9.820, p < 0.002$]. However, in this set of stimulus conditions, S-cone difference scores were not statistically significant [$F(1, 176) = 0.0921, p = 0.842$]. This may be because from Experiment 1 to Experiment 2 the size of the purple-patch effect increased from 3.3% to 4.3%, yet the size of the green-patch effect decreased from 4.2% to 2.6%. A MANOVA showed that none of the main effects we presented were statistically significant for l difference scores (i.e., relative L- and M-cone excitation) [$F(3, 174) = 0.333, p = 0.565$].

B. Discussion

Although surrounds that varied in both chromaticity and intensity reduced the effect size seen in Experiment 1 (when only intensity varied) by more than 50%, shadow compatibility still produced a stronger Adelson–Logvinenko[1,3] brightness illusion than shadow incompatibility. Interestingly, this effect was somewhat smaller in stimuli with adjusted cone-excitation ratios than with unadjusted stimuli. The reason for the decrease in effect size lies in the important distinction between lightness and brightness. In essence, a shadow interpretation of the data suggests that when observers inferred that the darker surrounds were due to a shift in illumination (i.e., predicted by their adjusting cone-excitation ratios[28,29]) they reduced the test intensity 26%. However, when they inferred that the darker surrounds also contained a shift in reflectance (i.e., predicted when they did not adjust cone-excitation ratios[28,29]), they reduced the test intensity 31%. We postulate that the additional 5% *darkening* is due to local contrast induction (a lightness effect), whereas the 26% *dimming* is due to global mechanisms that regulate illumination (a brightness effect). These ~5:1 (global:local) proportions have been found consistently in the achromatic literature.[12,42,44] More important, even this small effect is remarkable because Logvinenko[2] would have predicted no effect of adjusting cone-excitation ratios, because they do not alter contrast polarity. We attribute this effect to improved lightness constancy because observers were instructed specifically to match the rows in hue and saturation (i.e., lightnesses chromatic equivalent), as well as brightness.

By containing both an intensity difference and a chromatic difference, the stimuli used in Experiment 2 create ecologically plausible, albeit atypical, shadow conditions. For example, the forest floor can appear both darkened and slightly greener owing to overhead foliage. This phenomenology underscores how brightness judgments using dichromatic stimuli might evoke higher-order shadow-compatible mechanisms (e.g., brightness) that augment lower-level (i.e., lightness, or hue and saturation) processes.

These results agree with Metelli's work on achromatic transparency,[45] in that adjusting cone-excitation ratios in our chromatic shadow-compatible condition may be comparable to adding a cast shadow. For example, Logvinenko[1] found that with shadow-incompatible stimuli [Fig. 1(b)], the dark region may appear to be covered by a transparent overlay, but a shadow interpretation is not elicited. Since induction almost disappears in the shadow-incompatible stimulus, one possible conclusion is that the visual system corrects for darkening that is attributed to a different illuminant (e.g., a shadow) but not to darkening due to a darkening filter. This is congruent with the fact that in our shadow-incompatible examples the impression of a transparent filter not only darkens but also lightens. That is, the lighter background is darkened while the darker background is lightened. This would be represented as t in Metelli's model, which is always an intermediate value between the two backgrounds.[45] However, this interpretation relies on Metelli's use of an episcotister. It might not occur with a real filter or a shadow because the reflective component of filters or the shadow-compatible darkening due to a different level of illumination (e.g., a shadow) can only darken the background.[46] Another possible lower-level mechanism that might predict the translucent appearance of Logvinenko's[1] shadow-incompatible stimuli is Masin's rule of inclusion.[47,48]

5. EXPERIMENT 3

A. Results

In this experiment, the rows of test patches were always adjacent to the surrounds that changed across shadow-compatibility conditions, while the rows of comparison-patches were always adjacent to surrounds that remained fixed across shadow-compatibility conditions [Figs. 3(e) and 3(f)]. As in Experiment 1, a univariate ANOVA revealed that to match the comparison patches, observers changed the s value by 6.8% more in the shadow-compatible condition (solid circles) than in the shadow-incompatible condition (open squares) [$F(1, 176) = 17.772, p < 0.001$; Fig. 10, Table 3]. This result was

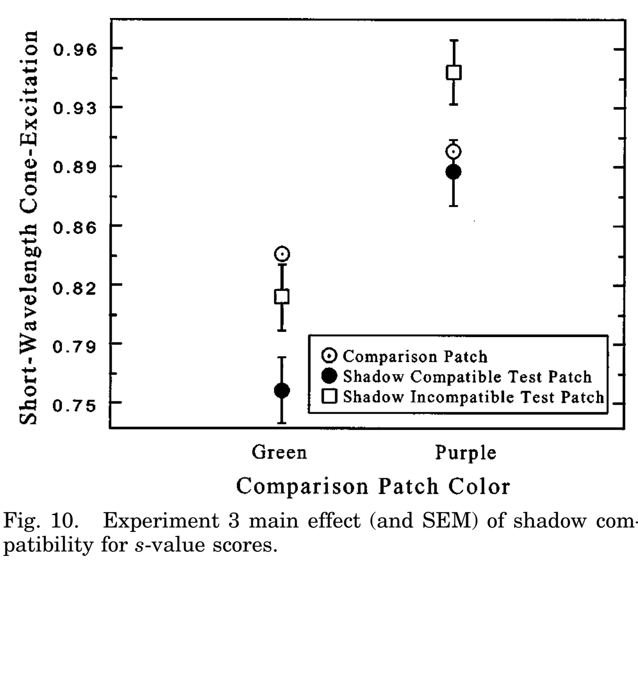


Fig. 10. Experiment 3 main effect (and SEM) of shadow compatibility for s-value scores.

comparable for both the green and the purple test patches. The green test patch had a mean *s*-value difference score of −0.052, and the purple test-patch had a mean *s*-value difference score of 0.015, which were reliably different. This difference produced a statistically significant main effect of test-patch color for the *s*-value difference score [$F(1,176) = 26.820, p < 0.001$; Fig. 10]. Moreover, the mean *Y*-value difference score was −5.338 cd/m^2 for the green test patches and 1.167 cd/m^2 for the purple test patches [$F(1,176) = 401.767,\ p < 0.001$; Table 3].

There was no statistically significant *s*-value difference [$F(1,176) = 1.449, p = 0.230$] between stimuli with adjusted and unadjusted cone-excitation ratios. A MANOVA revealed that none of the main effects we presented were statistically significant for l difference scores (i.e., relative L- and M-cone excitation) [$F(3,174) = 1.685, p = 0.172$].

B. Discussion

The systematic variations used in the chromatic stimuli of Experiment 3 [e.g., Figs. 3(e) and 3(f)] parallel what Logvinenko[1] considered his achromatic stimuli's relevant characteristics [Fig. 1(a)]. This allowed us to consider how judgments of brightness (in the achromatic domain) and hue, saturation, and brightness (in the chromatic domain) with shadow-compatible stimuli produce responses consistent with those evoked from the presence of a real shadow or filter. Most important, Fig. 10 demonstrates that our chromatic stimuli produce findings comparable to those found with the achromatic Adelson–Logvinenko illusion [see Fig. 1(a)].[1,3] For example, in the shadow-compatible condition the test patches within the more-yellowish surround appeared to contain more blue than the comparison patches within the more-bluish surround. This result is comparable to that obtained when the test patches within the darker surround appeared brighter than the comparison patches within the lighter surround of the Adelson–Logvinenko illusion.[1,3]

Independent of shadow compatibility, the green test patches within the more-yellowish surround typically appeared both brighter and bluer, or the green comparison patches within the more-bluish surround appeared both dimmer and yellower, or both. This pattern of results is similar to that found for related conditions in Experiment 2.

Although it is possible to have different chromaticities of illumination on each cube surface, it would be atypical. We therefore did not expect that observers would perceive an explicit shadow but would merely produce settings consistent with such an interpretation. This finding reinforces Helmholtz's[49] notion that the consequences of inferences regarding illumination, but not the inferences themselves, need be visible. The modest size of the effect leaves open the possibility that while our stimuli captures the essential distinction Logvinenko[1] made between achromatic shadow-compatible and shadow-incompatible stimuli, other chromatic constructions might activate different proportions of lower- and higher-level activity.

One important consequence of our specific construction is that the test- and comparison-cube tops are both simulated under a 5300° K illuminant. This illumination temperature should appear neither yellowish nor bluish.[36] Consequently, there should be no consistent local edge relationships with the cube tops' adjacent neighbors from which to infer a specific pattern of illumination. In contrast, the strips contain consistent shadow-compatible information, allowing the visual system to misperceive the strips as containing different illuminants. A shadow-compatibility hypothesis accounts for the influence of such a global effect on test- and comparison-patch regions that do not contain contradictory local edge information.

Interestingly, there was no significant difference between stimuli with adjusted and unadjusted cone-excitation ratios in Experiment 3. Thus only when an intensity border accompanied a chromatic border (Experiment 2) did cone-excitation-ratio invariance across surfaces enhance *lightness* constancy. Even then, adjusted cone-excitation ratios left S-cone *color* constancy unaffected. These results may reflect the fact that in nature, shadows are typically the result of a decrease in intensity. Consequently, equating cone-excitation ratios across chromatic borders without a concomitant intensity shift may be unwarranted.

6. CONCLUSIONS

Some vision researchers attribute specific visual phenomena exclusively to either low-, mid-, or high-level processes. Such distinctions would be misleading if, as we assert, altering *any* aspect of a scene (e.g., by adding a colored filter) alters *all* levels of processing. Furthermore, we propose that across levels, mechanisms produce shifts typically in tandem rather than in conflict. This consistency promotes unambiguous scene interpretation and increases the veridicality of representations. Finally, we assume that when matching two surfaces in hue, saturation, and brightness, observers minimize discrepancies in both local contrast and inferred illumination. Taken together, these perspectives make it impossible to eliminate consideration of local contrast when one is evaluating higher-order mechanisms. For example, increasing stimulus complexity enhances lightness constancy in complex displays (e.g., compare Arend and colleagues' center-surround[21] versus Mondrian[24] data). While such complexity suggests contributions from higher-level mechanisms, even this interpretation presumes concurrent activation of corollary local-contrast mechanisms.[43,44]

Incorporating Foster and Nascimento's[28] and Nascimento and Foster's[29] theory of equalizing cone-excitation ratios into our experimental design has allowed us to underscore how in shadow compatibility local contrast works in tandem with more global higher-order processes. For example, we did not measure lightness, because such a measure would have required telling observers that the cube tops were illuminated by different sources (or under a transparent filter). In fact, whether observers' responses were consistent with such an interpretation is precisely what the present study sought to determine. However, from previous achromatic research we predicted that had we been able to measure lightness, observers' settings should have remained roughly invariant, displaying constancy.[4,21,24] Though not being able to explicitly test this inference, the data presented in Fig. 9(d) support the interpretation that chromatic stimuli can evoke changes in local contrast mechanisms not available to comparable achromatic stimuli. Logvinenko's hypothesis[2] would predict no effect of adjusting cone-excitation ratios. This limits to the achromatic domain his conclusion that the only mechanisms that matter rely solely on ordinal information.

Instead, we measured hue, saturation, and brightness. These instructions were critical because they include both the level and the chromaticity of the inferred illumination, which relates directly to the phenomenology of inferring transparency and possibly shadows (e.g., if they appear tinted blue). Consistent with Arend and Reeves'[21] and Arend *et al.*'s[24] results obtained with chromatic stimuli, observers' brightness matches underestimate the amount of possible shift in the illuminant.

Our findings do support Logvinenko's[1] achromatic hypotheses, which predict that observers will make greater test-patch adjustments with shadow-compatible than with shadow-incompatible stimuli in the direction *toward* the brightness of their immediately adjacent surrounds. This pattern of results was observed for stimuli in which component patches varied in intensity only (Experiment 1), chromaticity only (Experiment 3), and both intensity and chromaticity (Experiment 2). Furthermore, this finding is in the same direction as one would observe in a comparable natural scene containing real transparent filters. In this case a dark neutral density filter would make the underlying cubes appear dimmer. However, if all the cube tops had identical luminance, then those beneath the filter would appear too bright. Observers would need to make adjustments to the intensity of these cube tops to correct this apparent discrepancy. This pattern of adjustment was observed in the current study, suggesting that observers estimated a greater difference in the level of illumination between the test- and comparison-patch regions with shadow-compatible than with shadow-incompatible stimuli. This principle held across all three chromatic variations of Logvinenko's achromatic wall-of-blocks stimuli,[1] demonstrating that preserving equal transversal luminance ratios and codirectional contrast invariances evokes shadow compatibility in the chromatic domain. On the other hand, our shadow-incompatible condition minimized this transparent quality. As with both Logvinenko's achromatic stimuli[1] and the present set of stimuli, replacing surfaces that abut either the test or comparison patches can alter local simultaneous contrast in the same direction as a perceived shift in the illuminant. It is therefore likely that local mechanisms also contribute to observers' adjustments. However, the fact that isochromatic yellow surrounds shifted observers' short-wavelength-cone setting more than eightfold compared with isochromatic blue surrounds quantifies that local induction is, at most, only part of a more complex process.[50]

Global models that account for transparency are one way to characterize our stimuli.[51–57] D'Zmura *et al.*[58] showed that the impression of transparency holds for equiluminant chromatic stimuli. This finding allows a translational model to predict how our approximately isoluminant chromatic stimuli might appear transparent as well. Moreover, our stimulus design can be tested against Westland and Ripamonti's[59] transparency model, which agrees with D'Zmura and colleagues' translational model.[58,60,61] That is, our stimuli are physically plausible if in Fresnel's equation [i.e., $k = (n - 1)^2/(n + 1)^2$] we set $n = 1$. This assumption makes it possible to relate our data to Westland and Ripamonti's[59] subtraction model, in which $P_i/Q_i = A_i/B_i$, since $k = 0$, given $k = 2(Q_iA_i - P_iB_i)/(P_i - Q_i)(A_i + B_i)$.[62] Unfortunately, we cannot test a convergence model of transparency because we cannot reduce either the luminance or the chromatic contrast in the transparent row (i.e., we kept $\alpha = 0$).[63,64] That is, our darker (i.e., transparent) row is formed by decreasing both instead of just one cube-surface intensity (Experiment 1), chromaticity (Experiment 3), or intensity and chromaticity (Experiment 2). However, if our stimulus design did allow for a reduction of contrast or chromaticity within the transparent region, k would increase. This would violate Westland and Ripamonti's[59] equal-cone-excitation-ratio model and possibly make an additive (e.g., D'Zuma's convergent)[58] model a better fit of the data.

As Foster and Nascimento[28] and Nascimento and Foster[29] would predict, adjusting cone-excitation ratios within each cone class produced a pattern of data consistent with better lightness constancy as well as an estimate of the illuminant better than that with unadjusted stimuli. We attribute this to the relationship between the physical qualities of luminance and reflectance and their psychological correlates (i.e., brightness and lightness, respectively, where apparent luminance (i.e., brightness) = apparent illumination (i.e., illumination) × apparent reflectance (i.e., lightness).[4] To drive the brightnesses and lightnesses of the cube tops in opposite directions could therefore simply require that cube tops of fixed luminance appear to be under different levels of illumination. This is exactly the phenomenon observed in Experiment 2.

This finding concurs with those found in several laboratories[63–66] that considered apparent illumination to be a form of transparency, with an inverse relationship between lightness and transparency for regions of constant luminance. It also agrees with Helmholtz's theory of inferred illumination[49] that accounts for the observation that adding white tissue paper over a saturated green patch makes a central gray patch appear reddish,[7,49] as well as Beck's observation that inappropriate border polarity simultaneously eliminates apparent transparency associated with scissioned surfaces.[65] These findings are especially interesting in that Bauml[67] showed that changes in a surface collection *per se* do not induce a substantial change in the effect that illuminant changes have on observers' settings.

The choice to simulate daylight illuminants reflects our assumption that the visual system evolved to discriminate sunlight's short-wavelength variations.[16,17,68] Baeuml[67] has also shown that color constancy deviations were due mainly to failures in adjusting S-cone signals.[69] Our choice of daylight illuminants fortuitously accentuated the unanticipated result of an S-cone shift (Experiment 1) in the same direction as Churma (his Fig. 1) would predict if a real shadow were present.[19] While the notion that this hue shift is due to observers' inference that shadowed regions should appear bluer is speculative,[19,20] the fact that the hue shift occurs only with a concomitant luminance edge (Experiment 1) warrants further investigation.

For example, eliminating the chromatic border eradicated the advantage of adjusting cone-excitation ratios (Experiment 1). This finding agrees with Oddo *et al.*,[70] who showed that perceived chromatic segregation is a function of cone contrasts and is unrelated to the similarities of the hues. Moreover, having only a chromatic border along an apparent transparency border without a corresponding intensity shift also negated any potential improvement of adjusting cone-excitation ratios (Experiment 3). This finding may reflect our lack of experiencing shadows as containing hue shifts without concomitant intensity shifts. The small but significant shift in S-cone excitation in the shadow-compatible condition with a chromatic-only display (Experiment 3) is noteworthy because it required using simulations only of daylight illuminations that differed by approximately CIE $x = 0.05$. This was the value that Craven and Foster[71] used to obtain performance levels of greater than 92% correct in observer's ability to discriminate whether changes in surface chromaticity were due to changes in reflectance or illumination.

Invariant cone-excitation ratios provide a simple means (e.g., similar to von Kries's adaptation[72]) of approximating whether there are systematic shifts in illumination, according to Foster and Nascimento[28] and Nascimento and Foster.[29] Although cone-excitation ratios across chromatic shadowed borders in natural scenes are not perfectly invariant, they are often close. Such ratios could therefore serve as an ecologically valid cue for distinguishing shifts in illumination from shifts in surface reflectance. This notion sets apart chromatic wall-of-blocks stimuli from their achromatic counterparts by highlighting their ability to reveal the conditions under which higher-level mechanisms such as shadow compatibility might operate in tandem with lower-level (i.e., ratio-sensitive) mechanisms.

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