Role of perceptual organization in chromatic induction

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Color matches between two small patches were made in a display containing ten larger regions of different chromaticities. The spatial organization of the ten regions was varied while keeping constant the immediate surround of each patch as well as the space-average chromaticity of the entire stimulus. Different spatial arrangements were designed to alter the perceptual organization inferred by the observer without changing the ensemble of chromaticities actually in view. For example, one arrangement of the ten regions was consistent with five surfaces under two distinct illuminations, with one edge within the display (an "apparent illumination edge") dividing the stimulus into two areas, one under illuminant A and the other under illuminant C. Another spatial arrangement had the ten regions configured to induce an observer to infer ten surfaces under a single illumination. When the ten regions were arranged with an apparent illumination edge, the patch within the area of illuminant C was perceived as bluer than when the same patch and immediate surround were presented without an apparent illumination edge. The results are accounted for by positing that observers group together regions sharing the same inferred illumination, with a consequent effect on color perception: A fixed patch-within-surround shifts in hue and saturation toward the perceived illumination. We suggest that the change in color perception in a complex scene that results from a difference in real illumination may be caused by the inferred illumination at the perceptual level, not directly by the physical change in the light absorbed by photoreceptors. © 2000 Optical Society of America [S0740-3232(00)00902-9]

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1. INTRODUCTION

The color of a light within a complex scene is not simply determined from the light's physical properties. Chromatic induction is well-known to alter color appearance when a light is viewed within a uniform chromatic surround.[1–4] Light beyond an immediate surround also affects color perception.[5,6] In natural viewing, the appearance of an object remains nearly stable *despite* a change in the physical light emanating from it when the change is due to a different illuminant. In general, theories that aim to explain color appearance include a variety of mechanisms, ranging from local ones (for example, receptoral gain and contrast at edges) to global ones (for example, discounting the inferred illumination of an entire scene). We focus here on global processes by using moderately complex fields that vary only those features of the stimulus that are some distance from the small patches to be judged in color. Local contrast at the edge of each patch and the space-average chromaticity within a $10° \times 10°$ surrounding region are held constant. The experiments are designed to vary the perceptual organization of the field by making only minimal, remote changes to the visual stimulus.

Perceptual organization can affect inferred illumination. The idea that the appearance of a surface depends on its inferred illumination has a long history. Helmholtz[7] argued that illumination differences are discounted even when not directly observable. Hering[8] showed that a shadowed area appears darker when a black line is drawn around its penumbra, presumably because the black line changes the perception of the shadowed area into a perceived surface. Conflicting ideas have been proposed regarding the properties of a scene that mediate inferred illumination. Judd[9] postulated that the "impression of illumination" is the average brightness of a scene.[10] Logvinenko and Menshikova[11] and Logvinenko,[12] on the other hand, claim that brightness is not an appropriate index of apparent illumination. Several studies claim to provide indirect measurements of perceived illumination and/or perceived lightness,[13–21] and two studies attempted to measure directly the perception of achromatic illumination.[14,20] We know of no study where the chromaticity of apparent illumination was measured.

In natural viewing, two or more illuminations occur frequently because of shadows or multiple sources of light. This may occur with either a sharp boundary or an illumination gradient. In both cases regions must be grouped according to their common illumination in order to discount it. Grouping can depend on subtle cues and can change even with a constant stimulus.[23] We use here a collection of chromatic stimuli configured in various ways that range in appearance from bluish to yellowish. We test whether color perception depends on minimal changes in the spatial configurations that are designed to alter perceptual grouping. At the most basic level, these experiments test whether color appearance can be explained by knowing all the chromaticities in view, irrespective of their locations (note that our manipulation of locations does not affect local contrast at the edge of each patch, which is held constant). Varying only locations does not, of course, alter the spatial average, range, or ensemble of the luminances and the chromaticities in view, so if the spatial configurations affect appearance, then these statistical summaries of the stimulus would be insufficient for a complete theory of color perception. In this case the perception of illumination might be considered an emergent feature[24] that depends on the spatial relations among the various chromaticities. *What* is perceived would depend on *where* stimuli are perceived.[25]

The edge(s) in a scene inferred to result from a difference in illumination can be used to group regions with the same perceived illumination.[26] The term "apparent illumination edge" was introduced to describe a physical chromatic and/or luminance edge that may be parsimoniously interpreted to result from a difference in illumination.[22] The term borrows from the concept of apparent motion,[27] where an object is not really in motion but rather is spatially displaced across successive presentations. The visual system interprets this stimulus sequence as a single moving object, which is a parsimonious, ecologically valid perceptual interpretation of the stimuli. Analogously, an apparent illumination edge allows a parsimonious, ecologically valid interpretation of many regions with different chromaticities in view simultaneously. In one of the following experiments, for example, a particular chromatic edge in a complex display could be due to a single change in illumination falling across several surfaces or instead be due to several specific quantitative changes in reflecting surfaces that are lined up precisely along the edge. Neither interpretation is preferred on purely physical grounds (similarly, in apparent motion a stimulus sequence could be either a single object in motion or many distinct objects each of which appears in only a single frame). An edge in the stimulus is considered an apparent illumination edge if it provides an economical and ecologically valid description of the complete display.

The experiments here vary the light in only those parts of the stimulus that are outside the regions surrounding the small patches that are matched in color. The influence of these remote lights is called a context effect.[28,29] An important feature of our experimental design is that the remote contextual factors are varied without changing the overall retinal stimulation. This is unlike previous studies of adaptation and constancy that varied the illuminating light to determine the degree to which the illumination is discounted.[30–34] Also, the stimuli here have similar chromatic gradients in the 10°×10° area that surrounds each patch matched in color. This avoids the difficulty inherent in asymmetric matching of a test patch within a large homogeneous surround (or no surround) to a comparison patch within a complex chromatic field.

In considering these experiments, it is important to bear in mind that all but the baseline conditions include ten distinct regions varying in Judd (x', y') chromaticity from (0.23, 0.28) to (0.45, 0.44). These are complex stimuli readily perceived as surfaces, as are Mondrian displays.[35] An experimental manipulation that varies perceptual organization may affect the perceived colors of the regions but not whether the display is perceived as surfaces under illumination. These various spatial configurations, therefore, are *not* expected to shift the measurements from isomeric matches (as would occur if all surrounding light were extinguished, so that only the two matching patches were in view) to measurements that take account of an inferred illuminant (for example, the "paper" matches of Arend *et al.*[32]).

2. METHODS

A. Observers

Three observers were tested. All had normal or corrected acuity (20/20) and normal color vision as determined from the Farnsworth–Munsell 100-hue test and Rayleigh matches. Author JS, a 39-year-old male, was knowledgeable about the experimental paradigm and had experience making brightness judgments using complex achromatic displays. Observer AL, a 23-year-old male, had experience making brightness judgements but was naive regarding the experimental design. Observer BD, a 20-year-old female, was naive regarding the experimental design and had no experience making either achromatic or chromatic judgments.

B. Apparatus

Chromatic patterns were generated by using a Macintosh IIcx computer and were presented on an accurately calibrated Nanao T560i 17-in. color monitor. The 832×624-pixel screen had a scan rate of 75 Hz noninterlaced. The chromaticity of each phosphor was measured spectroradiometrically. The R, G, and B guns were linearized by using an 8-bit lookup table. The chromaticity and the luminance set by the software did not vary appreciably over the effective viewing area. Chromaticity and luminance were approximately constant (±3%) within the central region of the screen that displayed the test and comparison patches.

C. Stimuli and Procedure

Observers viewed the monitor at a distance of 67 cm in a dark room. The CRT displayed the chromatic patterns on an otherwise dark screen. In a baseline condition, a uniform surround was 10.5° × 10.5° [Fig. 1(a)]. A 1.25° square comparison patch (denoted C) was centered within the right surround. The comparison patch was set by the computer from trial to trial to one of eight Judd (x', y') chromaticities: "green" ($x' = 0.255$, $y' = 0.426$), "blue" ($x' = 0.258$, $y' = 0.297$), "purple" ($x' = 0.290$, $y' = 0.232$), "white" ($x' = 0.314$, $y' = 0.324$), "pink" (x'

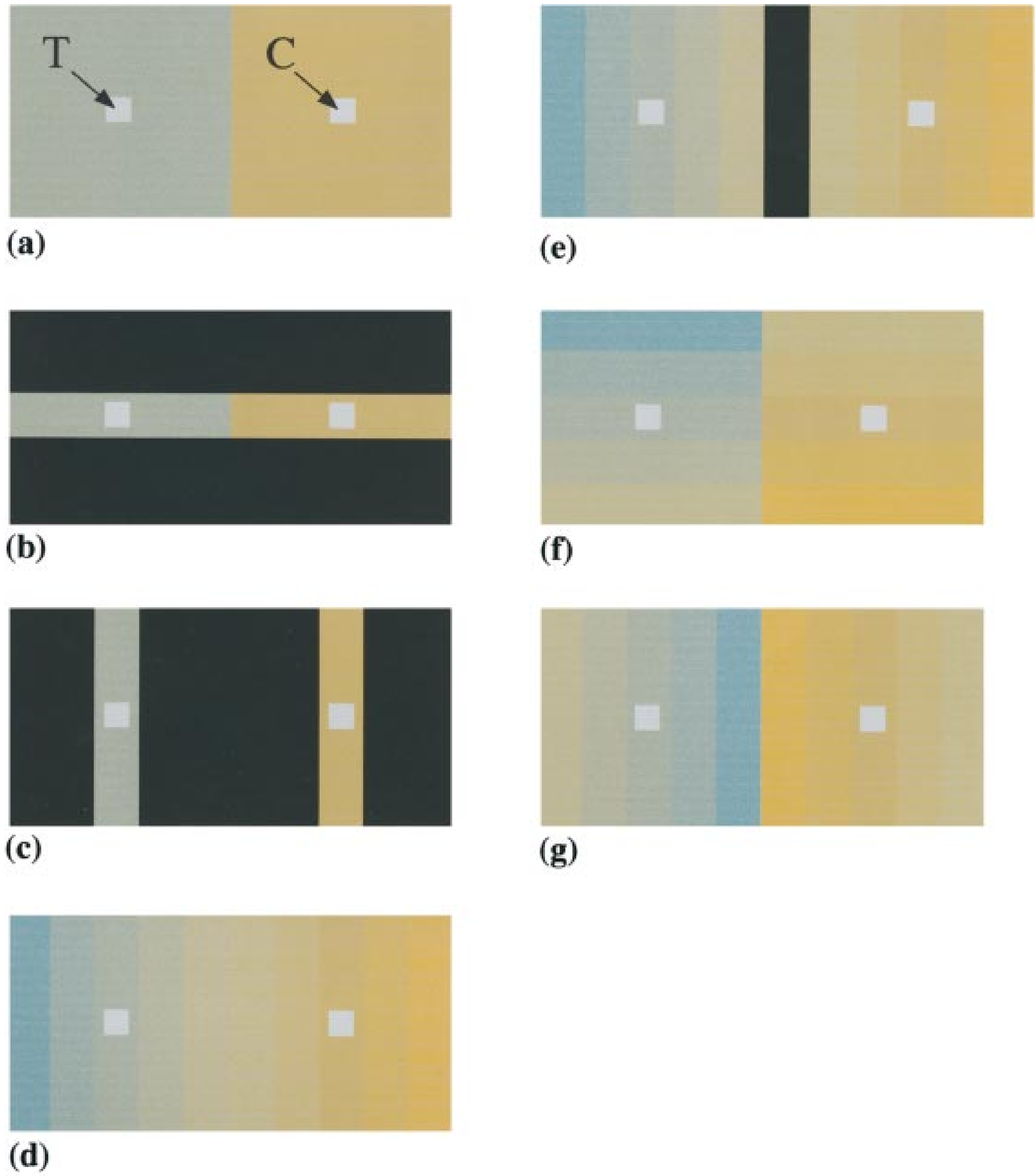

Fig. 1. (a) Two abutting uniform 10.5° × 10.5° surrounds. The left-hand test surround is Munsell B 5/2 under illuminant C, and the right-hand comparison surround is Munsell B 5/2 under illuminant A. The test and comparison patches are 1.25° squares. (b) Two abutting horizontal 2.1° × 10.5° stripe surrounds [identical in chromaticity with the test and comparison surrounds of (a)]. (c) Two vertical 2.1° × 10.5° stripe surrounds [identical in chromaticity with the test and comparison surrounds of (a)]. (d) Ten vertical 2.1° × 10.5° stripes (chromaticities shown in Fig. 2). The stripes appear as ten different surface colors graded from blues through grays through yellows. (e) Ten vertical 2.1° × 10.5° stripes as in (d) grouped into right and left halves and separated by a 2° dark gap. (f) Ten stripes from (d) rotated 90° clockwise around the test and comparison centers as pivot points (see the text). (g) Ten vertical 2.1° × 10.5° stripes as in (d) grouped into right and left halves but reversed in sequence (see the text).

$= 0.367$, $y' = 0.322$), "yellow" ($x' = 0.379$, $y' = 0.428$), "orange" ($x' = 0.452$, $y' = 0.424$), or "red" ($x' = 0.506$, $y' = 0.316$). The order of presentation was randomized. A 1.25° square test patch (denoted T) was centered within a 10.5° × 10.5° left surround. The luminances of the test and comparison patches were held fixed at ~20 cd/m^2. Observers used a joystick to adjust the chromaticity of the test patch. To facilitate precision, observers could either increase or decrease the step size at will by the press of a button. Pressing another button signaled that a satisfactory match had been achieved, at which point the test chromaticity was recorded and the trial ended. Between trials the test and comparison patches returned to the chromaticity of their immediate surround for three seconds. Then the next trial began. Each session took approximately one hour.

Observers participated in several practice sessions before beginning the reported measurements. They maintained a stable head position with a chin rest. Observers dark adapted for three minutes and then light adapted for three minutes to a uniform field at the average of the test- and comparison-surround chromaticities and luminances ($x' = 0.274$, $y' = 0.305$, and $x' = 0.405$, $y' = 0.413$, both at ~ 20 cd/m^2). Then the test and comparison patches were presented.

Observers used a method of adjustment to vary the chromaticity of the test patch (T) to match the appearance of the comparison patch (C). They were told to adjust the test patch to appear identical to the comparison patch in hue and saturation.[31,32] They also were told to spend approximately the same amount of time looking at the right and left halves of the display by alternating their gaze between the two halves approximately every two seconds. The stimulus was large by design: The test and comparison patches were separated by 10° to minimize local adaptation caused by steady fixation and to encourage eye movements across the center of the display. The measurements showed little variability, suggesting that adaptation was stable.

No more than two experimental conditions were embedded in a single session. Three repetitions of each comparison-patch chromaticity within each condition were presented in a session. The mean of these three repetitions within a session was taken as the measurement for that session. No more than two sessions were run on the same day. The means and the standard errors shown in the plots in Section 3 are based on repeated measurements from three separate sessions.

3. RESULTS

A. Experiment 1: Uniform Surrounds

Two identical lights differ in appearance when surrounded by uniform fields at different chromaticities. This is the well-known phenomenon of simultaneous contrast.[1,3,37] Measurements were made with the use of uniform surrounds to provide baseline values for each observer. In this experiment [Fig. 1(a)], the test patch on the left was surrounded by a $10.5° \times 10.5°$ uniform "blue" field ($x' = 0.274$, $y' = 0.305$). The comparison patch on the right was surrounded by a $10.5° \times 10.5°$ uniform "yellow" field ($x' = 0.405$, $y' = 0.413$).

Figure 2 shows the Judd chromaticities of the two surrounds. The left test-patch surround was a simulation of Munsell paper 5 B5/2 under illuminant C, while the right comparison-patch surround was a simulation of the same Munsell paper under illuminant A (arrows in the figure). Note that observers might interpret the two surrounds as having the same reflectance under two different illuminations, or as having different reflectances under a single illumination, or as being different in both illumination and reflectance.

When the chromaticity of the test patch was equal to the chromaticity of the comparison patch, the test within the "blue" surround appeared too yellowish, as expected. Observers, therefore, set the test to a different chromaticity from that of the fixed comparison patch to achieve a hue and saturation match (compare circles with squares with cross in Fig. 3). Overall, both chromaticity coordinates of the test tended to decline, which is generally a shift toward the bluish part of the chromaticity diagram.

In preparation for more complex configurations than these two $10.5° \times 10.5°$ uniform surrounds, the surrounds were reduced in height from 10.5° to 2.1°. We refer to this stimulus as the two-row configuration [Fig. 1(b)]. In a further baseline condition, the two large surrounds were reduced in width from 10.5° to 2.1° while retaining the previous separation between test patch and comparison patch [Fig. 1(c)]. This produced a large dark gap between the surrounds in this two-column configuration. The measurements were very similar in all three of these conditions (Fig. 4).

The visual impression of no difference between these spatial configurations is supported by statistical results. A nonmetric binomial statistic is used here to test whether two conditions differ in the magnitude of chromatic induction. Greater induction is defined as a test-field measurement displaced farther from the chromaticity of the fixed comparison field (squares with cross in all data plots). The nonmetric test avoids the questionable assumption that chromaticity coordinates are interval-scale values. The nonmetric test is particularly appropriate here because the various experimental conditions shift the measurements approximately in the same direction from the fixed comparison field. First, compare the two-row and two-column configurations (diamonds and triangles, respectively, in Fig. 4). Twenty-four comparisons can be made from Fig. 4 (eight comparison-field chromaticities matched by each of the three observers). A systematic difference between the two-column and two-row configurations would be indicated if substantially more than half of the 24 comparisons showed greater induction for one of these two configurations. In Fig. 4, 11 of 24 (46%) of the measurements show greater induction with the two-column configuration. This value is at chance ($p > 0.50$, two-tailed). Similarly, consider whether the larger $10.5° \times 10.5°$ surrounds caused the greatest induction. The probability of observing greatest induction from the larger surround by chance is 0.33 because there are three spatial configurations in all: larger surround, two-row, and two-column. The measurements show greatest induction from the larger surround in 11 of

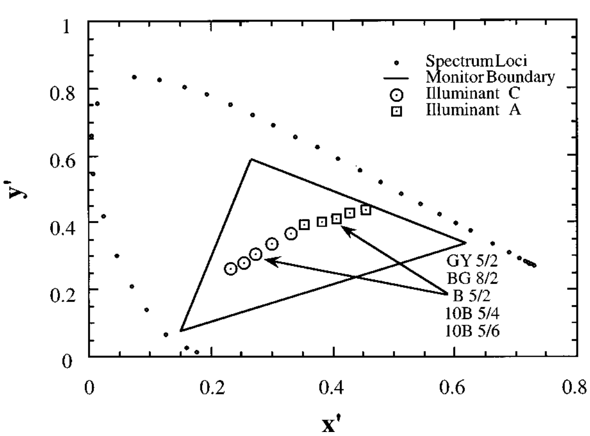

Fig. 2. Chromaticities of the ten $2.1° \times 10.5°$ stripes. The chromaticities are derived from five Munsell papers under illuminant C (circles) and illuminant A (squares): 10B 5/6 ($x_C = 0.232$, $y_C = 0.264$; $x_A = 0.353$, $y_A = 0.392$), 10B 5/4 ($x_C = 0.254$, $y_C = 0.280$; $x_A = 0.383$, $y_A = 0.401$), B 5/2 ($x_C = 0.274$, $y_C = 0.305$; $x_A = 0.405$, $y_A = 0.413$, BG 8/2 ($x_C = 0.300$, $y_C = 0.337$; $x_A = 0.428$, $y_A = 0.427$), and GY 5/2 ($x_C = 0.331$, $y_C = 0.367$; $x_A = 0.454$, $y_A = 0.437$). Judd spectral loci are represented by small dots, and the monitor gamut is enclosed by the triangle.

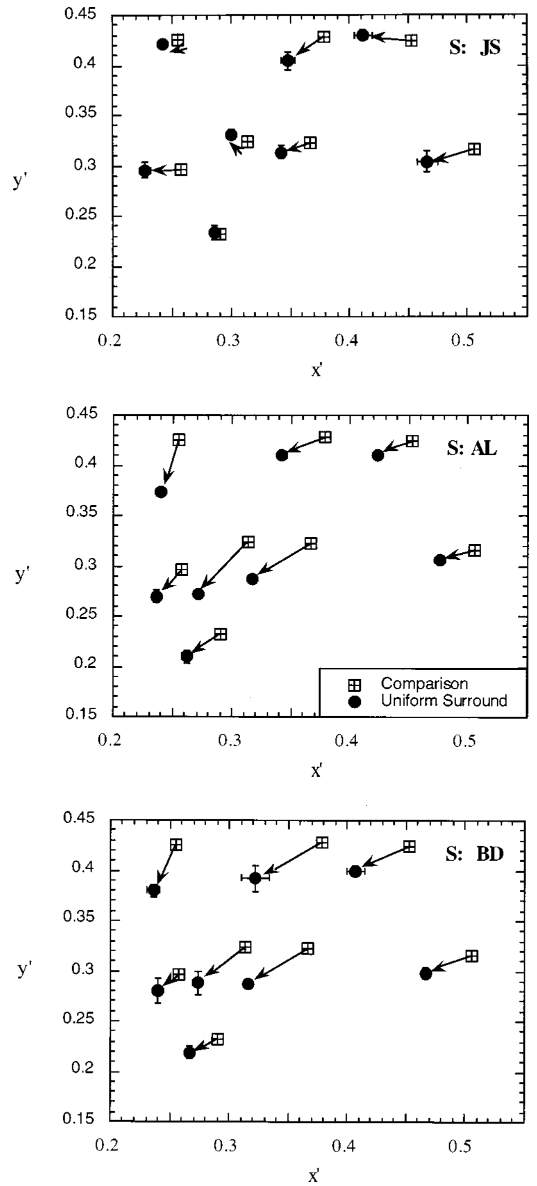

Fig. 3. Hue and saturation matches (in Judd space) between test T (circles) and the eight comparison patches C (squares with cross) with use of the two large uniform surrounds. Here and in the subsequent figures, the plots from top to bottom correspond to observers JS, AL, and BD.

24 matches, which again is not reliably different from chance ($p > 0.10$, one-tailed). Overall, there is no statistically reliable difference between any of the spatial configurations of Fig. 4.

B. Experiment 2: Ten Vertical-Stripe Surrounds

Surrounds with ten stripes were used to examine changes in color appearance that result from various spatial arrangements of a fixed set of chromatic stimuli [for example, Fig. 1(d)]. Each chromaticity was presented in a $10.5° \times 2.1°$ rectangular stripe. To preserve local contrast across all experiments, the stripe containing either the test or the comparison patch had the same chromaticity as that used above for surrounds.

The eight additional stripes had chromaticities that were simulations of four Munsell papers under either illuminant A or illuminant C (Fig. 2). The Munsell papers were chosen so that the ten stripes were graded in chromaticity. Further, the space-average chromaticity of the five papers under illuminant C ($x' = 0.278$, $y' = 0.311$) was very close to that of the uniform region that surrounded the test patch in all experiments ($x' = 0.274$, $y' = 0.305$). These five stripes were presented in the $10.5° \times 10.5°$ area centered on the (left) test patch. Similarly, the space-average chromaticity of the five papers under illuminant A ($x' = 0.405$, $y' = 0.414$) was near the chromaticity of the uniform region that surrounded the (right) comparison patch ($x' = 0.405$, $y' = 0.413$). These five stripes were in the $10.5° \times 10.5°$ area around the comparison patch. The stripes were very similar in luminance (~20 cd/m^2) but should not be considered equiluminant for each observer. The experimental design aimed to equate the space-average spectral

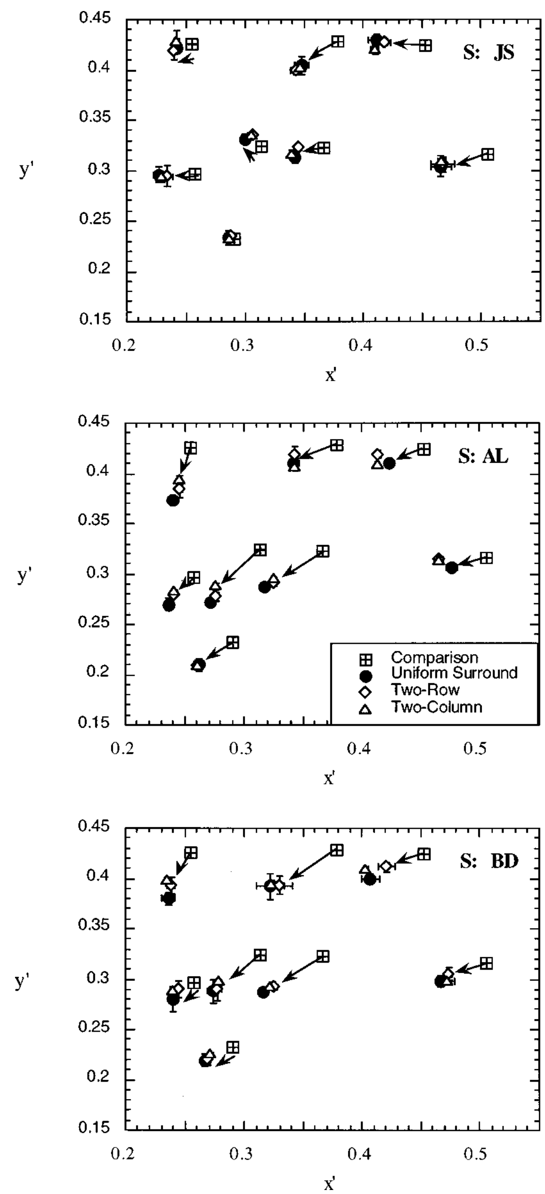

Fig. 4. Hue and saturation matches (in Judd space) for two large uniform surrounds (circles), the two-row uniform horizontal surrounds (diamonds), and the two-column uniform vertical surrounds (triangles).

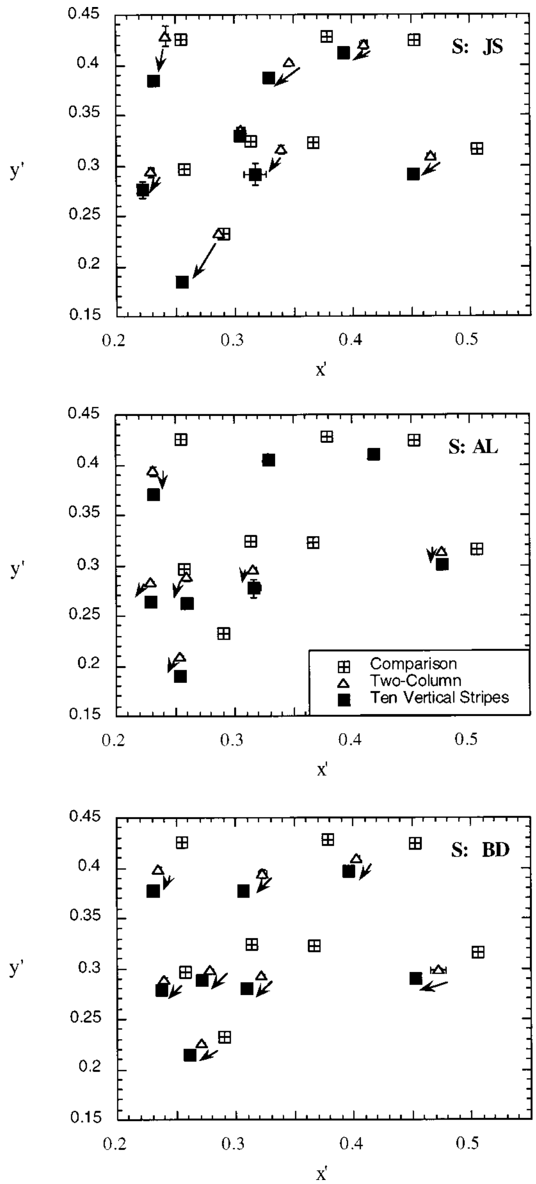

Fig. 5. Hue and saturation matches (in Judd space) for the two-column uniform vertical surrounds (triangles) and the ten-column vertical surrounds (filled squares).

distribution of light in each 10.5° × 10.5° striped field to the light in the larger uniform field used in the previous experiment. This equality of spatial averages would have been lost if the luminances of individual stripes had been adjusted for each observer. The complete set of ten stripes formed a reasonable perceptual continuum, appearing as ten colors graded from blues to yellows [Fig. 1(d)].

Consider the effect of increasing the number of distinct chromaticities in the surround from two to ten. Compared with the hue and saturation matches made with the two-column configuration (triangles in Fig. 4 and replotted in Fig. 5), matches made with the ten vertical stripes showed a further shift in the test toward the bluish part of the chromaticity diagram (Fig. 5, solid squares, $p < 0.002$, two-tailed). The matching test chromaticities found with only a uniform surround appeared too yellowish when all ten chromaticities were in view. Note that these measurements reject the hypothesis that chromatic induction depends on only the spatial average of surrounding light. Comparing specifically the measurements with ten vertical stripes with measurements with the 10.5° square uniform surrounds shows that the former caused greater induction ($p < 0.025$, two-tailed). Overall, increasing the complexity of the background, while holding constant (1) the space-average chromaticity in a 10.5° × 10.5° area around each patch and (2) the immediate local contrast of each patch, shifts color matches farther from a physical match. Chromatic induction is enhanced by the added chromaticities in areas that are outside the contiguous surround, a clear context effect.

One difference between the two-column and ten-vertical-stripe conditions is the dark separation between the two-column surrounds [compare Figs. 1(c) and 1(d)]. We examined whether the difference in induction found in these two conditions could be due to a dark gap rather than to a difference in the richness of chromaticities in view. Measurements were made with ten vertical stripes but with the five left stripes separated from the five right stripes by a 2° dark gap [Fig. 1(e)]. In Fig. 6, results with ten stripes presented in separated halves are compared with measurements from the two-column condition. The chromaticity richer ten-stripe stimulus with the gap still caused greater chromatic induction than the two-column condition ($p < 0.025$, two-tailed). Further, a comparison of the results with ten vertical stripes either with or without the gap revealed differences at the level of chance: Greater induction without the dark separation was found in 12 of 24 measurements.

C. Experiment 3: Ten Horizontal-Stripe Surrounds

To examine the influence of an apparent illumination edge on color perception, we rearranged the ten vertical columns used in experiment 2 [Fig. 1(d), no gap]. The five left columns were rotated 90° clockwise by using the test's center as a center of rotation, and similarly the five right columns were rotated 90° about the center of the comparison patch. The complete stimulus was now composed of left and right sets of five horizontal stripes, with a vertical apparent illumination edge between the left and right halves of the display [Fig. 1(f)]. The entire stimulus could be interpreted parsimoniously as five horizontal surfaces, with the left half under illuminant C and the right half under illuminant A. Note that the chromaticities of the stripes in the 10.5° × 10.5° area surrounding the test patch, and in the 10.5° × 10.5° area surrounding the comparison patch, are the same in Figs. 1(d) and 1(f), thus keeping constant the visual stimulus within 5° of each small patch (except for rotation). The spatial rearrangement of the stripes, however, produces an apparent illumination edge in Fig. 1(f).

Compared with the ten-vertical-stripe condition, the ten horizontal stripes caused observers to set test-patch chromaticities back toward the comparison-patch chromaticities, which is away from the bluish part of the diagram ($p < 0.001$, two-tailed) (in Fig. 7, compare circles with solid squares replotted from Fig. 5). This means that the rotation resulting in Fig. 1(f) makes the hue and the saturation of the (left) test patch more bluish, or the

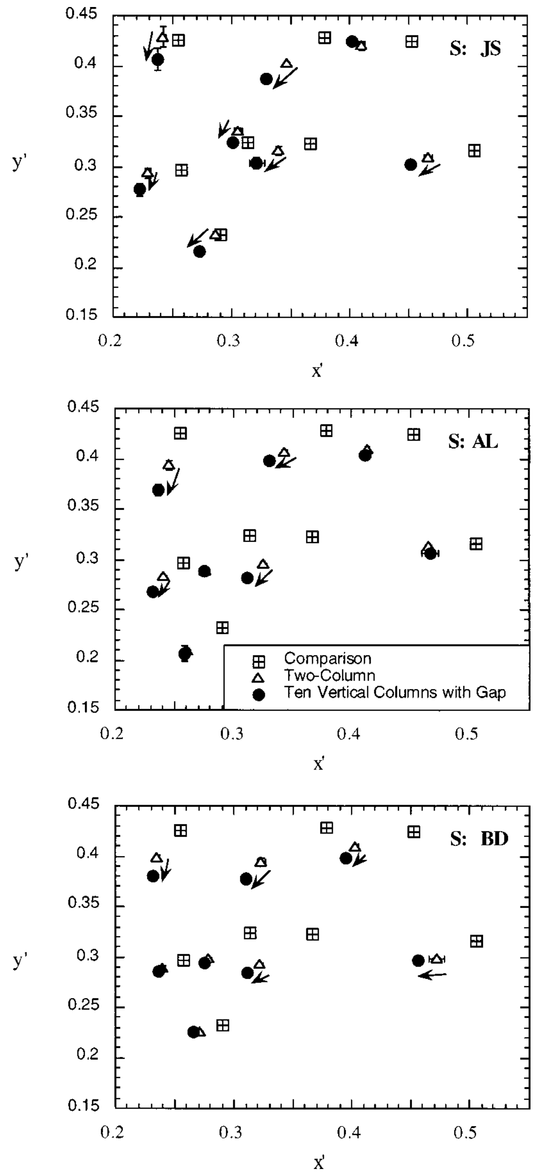

Fig. 6. Hue and saturation matches (in Judd space) for the two-column uniform vertical surrounds (triangles) and the ten-column vertical surround with a 2° dark gap (circles).

hue and the saturation of the (right) comparison patch more yellowish, or both. This is precisely what would happen if light from real "bluish" illumination from source C fell on the (left) test patch and illumination from real "yellowish" illumination from source A fell on the (right) comparison patch. The differences between the circles and the squares in Fig. 7, however, result only from rotating each half of the display by 90°, without otherwise changing the stimulus.

If observers were to treat the single vertical edge dividing the two halves of Fig. 1(f) as a reflectance edge, then the hue and the saturation of the test and comparison patches would depend on only local contrasts across the image and a single inferred illumination. If, however, the edge between the halves is perceived to be an illumination edge, then the hue and the saturation of the test and comparison patches may also be affected by the specific inferred illumination falling on each small patch. In general, changing the spectral composition of *real* illumination changes the light falling on a surface and therefore alters the light from the surface reaching the eye. This shift in retinal stimulation might be thought to be the cause of a shift in hue and saturation. In these experiments, however, there is no change in the chromaticity of the stimuli. A simple spatial rearrangement of the lights, chosen to alter perceived (but not real) illumination, shifts hue and saturation in the direction of a real change in illumination.

D. Experiment 4: Large-Contrast Edge versus Apparent Illumination Edge

In a final experiment, we sought to induce perceptual grouping without introducing a chromatic edge that permits a parsimonious interpretation of the ten chromaticities. The ten-vertical-stripe field [Fig. 1(d)] was modified by reversing the left-to-right order of the five stripes in

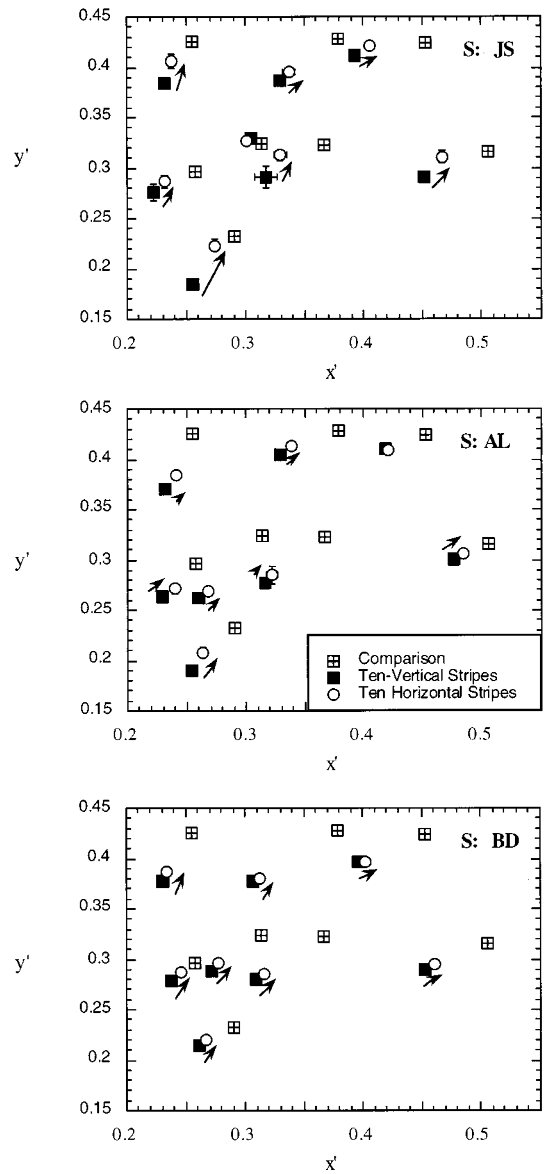

Fig. 7. Hue and saturation matches (in Judd space) for the ten-column vertical surround (filled squares) and the ten-row horizontal surround (circles).

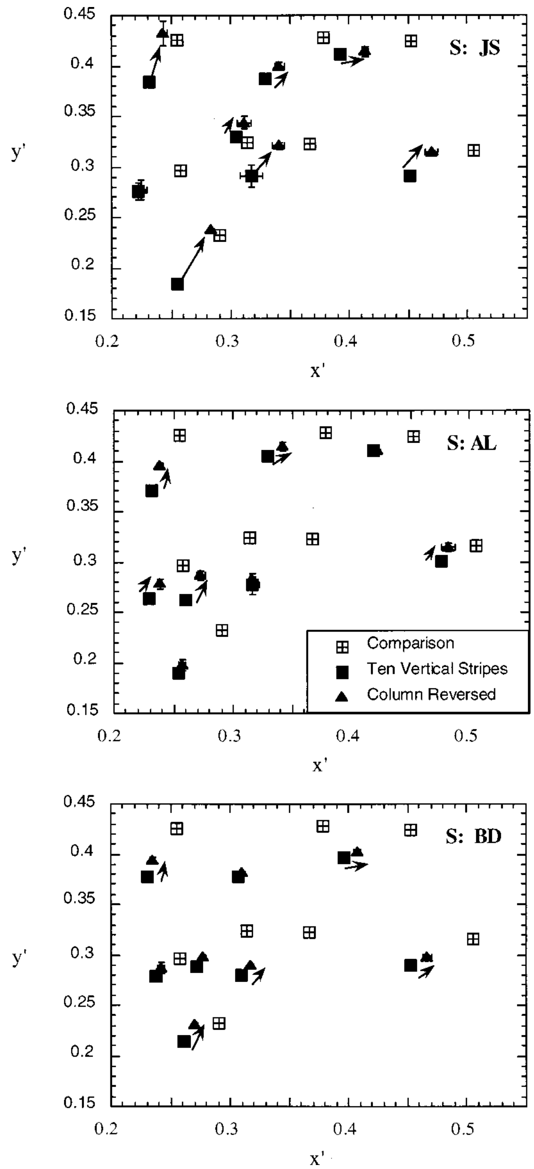

Fig. 8. Hue and saturation matches (in Judd space) for the ten-column vertical surround (filled squares) and the ten-column vertical-reversed surround (triangles).

the left half and by similarly reversing the five stripes in the right half [Fig. 1(g)]. This preserved the features of the stimulus in the 10.5° × 10.5° area around each patch (and, of course, the local contrast around each patch), but now the central vertical edge had much higher chromatic contrast than before. If regions with weak chromatic contrast are grouped together and segregated by a boundary of much greater chromatic contrast, then this stimulus should shift the previous results with ten gradually varying stripes [Fig. 1(d)], as did the ten horizontal stripes (see Fig. 7).

Color matches with the ten-vertical-stripe field containing a central edge of higher chromatic contrast [Fig. 1(g)] are shown in Fig. 8. These measurements (triangles) are compared with results with the ten-vertical-stripe stimulus containing only weak chromatic edges (solid squares, replotted from Fig. 5). Adding the high-contrast central edge shifts the measurements back toward the chromaticity of the comparison patch ($p < 0.001$, two-tailed). Results with the high-contrast central edge are very close to those from the previous experiment with ten horizontal rows that form an apparent illumination edge (circles in Fig. 7).

4. DISCUSSION

A. Classes of Models Inconsistent with the Results

These experiments report asymmetric color matches made within modestly complex contexts composed of ten distinct chromatic regions. Various spatial arrangements of the ten regions were designed to alter the perceptual organization of the complete display without changing low-level features of the stimulus. With respect to low-level descriptions, each patch judged in color was within a 10.5° × 10.5° surrounding region with a constant spatial average of light. The local surrounding light at the edge of each patch was also held constant. The spatial arrangements of the ten chromaticities were varied in most experiments by only rotating or left–right-reflecting the chromaticities filling the 10.5° × 10.5° area surrounding each patch [compare Figs. 1(d), 1(f), and 1(g)]. These spatial variations do not affect the predictions of any model of chromatic induction that includes radial symmetry with respect to light surrounding a test field (out to 5.25° from the test). Yet, these minimal changes caused significant shifts in color perception.

We specifically considered hue and saturation matches in variously configured complex scenes because these perceptual qualities depend on illumination. Perceived surface color, on the other hand, ideally is independent of illumination. There is no classical expectation of the change in hue and saturation caused by perceptual regrouping of regions inferred to share common illumination.

At the empirical level, the results show the importance of remote spatial relations within a large visual stimulus. Chromatic induction from these complex fields cannot be accounted for fully by knowing only the sizes, the chromaticities, and the proximities of the various lights in view. This implies that the spatial average (weighted or unweighted) (e.g., Valberg and Lange-Malecki[38]), the extremes (e.g., Wesner and Shevell[29]), and even the enumeration (e.g., Maloney and Wandell[39]) of chromaticities in view are insufficient to predict chromatic induction. Instead, more specific spatial relations among stimuli in a complex display affect color perception. *What* hue and saturation are perceived depends on *where* the lights are located with respect to one another. This argues against a strict separation between one neural stream, projecting occipito-temporally, that determines what objects are in view and a second stream, projecting occipito-parietally, that determines where the objects are located in space.[40,41]

B. Long-Distance Interactions

The regions' spatial relations that affect color perception operate over long distances. Local receptive-field properties cannot account for the results. Each of the ten chromatic regions here is relatively large (10.5° × 2.1°) and equal in size. The patches judged in color always were centered within a uniform surrounding region of this size (or larger) that was held throughout at a constant chromaticity and luminance. Further, rotating or left–right-reflecting the five regions around each patch did not alter any chromaticities, contrasts, or proximities to patch within the $10.5° \times 10.5°$ area around each patch. The changes in color perception observed in Figs. 7 and 8 [stimuli in Figs. 1(d), 1(f), and 1(g)] result from the distant differences at the center of the whole 21°-wide stimulus.

C. Perceptual Grouping

The spatial arrangements here were designed to affect the perceptual grouping of the ten chromatic regions. In one case the regions were presented with an apparent illumination edge, as defined in Section 1, which allowed the left and right halves of the display to be interpreted as areas with identical objects under different illuminations [Fig. 1(f)]. In a second case, the ten chromatic regions were arranged so that each half of the display contained edges of similar contrast, with a central edge of much higher contrast [Fig. 1(g)]. The results were similar in both cases and showed a shift in color perception compared with an arrangement with the ten regions forming a smooth perceptual continuum [Fig. 1(d)], which was designed not to invoke subgroups of the ten regions. Further, note that a color shift was not found when the two halves of the display were grouped *explicitly* by adding a dark region between them [Fig. 1(e) versus Fig. 1(d)]. We interpret these results to show that *perceptual* grouping is the critical factor mediating the changes in color perception. Of course, perceptual grouping can result from multiple processes.[42]

The interplay among perceptual grouping, inferred illumination, color perception, and object segmentation may be complex. On the one hand, a contribution of color vision to object segmentation is well appreciated. D'Zmura and Lennie[43] propose that a "purpose of color vision [is] an important role in the discrimination among objects" (p. 1666). According to Thompson *et al.*,[44] "color vision contributes to the task of segmenting the visual scene into regions of distinct surfaces and/or objects" (p. 17). Both of these views concern segmentation by object color, which depends on surface reflectance, so grouping stimuli that share a common illumination would be a primary aspect of successful object segmentation. A common illumination must be discounted for only those regions that share it. Further, the specific common illumination inferred depends on the lights in view that determine it, so grouping affects the lights used to infer a common illumination. The actual illuminations inferred for different regions, in turn, can also affect object segmentation, as when an illumination edge (real or apparent) falls across a single object [e.g., Fig. 1(f)].

The notion that different reflecting properties of multiple surfaces will affect the color perception of a test patch is not new. For example, when Bauml[45] (his Fig. 7) changed the reflections of a collection of surfaces while holding the collection's mean reflectance constant under a variety of illumination conditions, an embedded test surface's hue and saturation were altered. This is consistent with the idea that perceived illumination across an entire collection of objects depends on the surface reflectances that form that collection. The observations here use the *same* collection of chromaticities to alter the perceived illumination of a region by varying their spatial organization. Any suggestion that the visual system's adjustment to changes in illumination does not vary with the surface collection[46] must be tempered by the observation that a fixed collection has a different effect on color perception, depending on the spatial arrangement.

As the number of surfaces under a single illumination increases, the estimate of the illumination can be expected to improve.[47] We used only five surfaces under each (simulated) illuminant, so larger differences may be possible with a broader array of surfaces. The experiments here were designed to manipulate perceptual grouping. It is tempting to interpret them as showing effects of different inferred illuminations falling on distinct regions in view, though no direct measurements were made of perceived illumination (but see Subsection 4.D).

D. Comparison with Brightness Measurements

In a previous study,[22] we measured the brightness of small patches embedded in achromatic fields similar to those in Fig. 1. Ten achromatic stripes, similar in shape to those in Fig. 1, were presented in various spatial configurations. As here, some configurations of the ten stripes included an apparent illumination edge, so the ten achromatic regions could be interpreted parsimoniously as five surfaces, with half of each surface under a different illumination. The actual ensemble of achromatic lights in view (and the luminance of the light surrounding each patch) was kept constant. Only the spatial configurations were varied in designs chosen to affect perceptual grouping.

The brightness measurements are in accord with the color results reported here. Configurations with an apparent illumination edge yielded brightness matches that were distinct from configurations without one [the achromatic equivalent of comparing Figs. 1(d) and 1(f)]. The results showed that the brightness of a patch shifted in the direction of the apparent illumination; that is, a patch appeared brighter when under higher apparent illumination. This is qualitatively similar to the shifts here in color perception: The color appearance shifted in the direction of the apparent illumination.

In the brightness study, we also determined whether naïve observers perceive more than one source of illumination when a configuration had an apparent illumination edge (Table 1 in Schirillo and Shevell[22]). Subjects who did not participate in the main brightness experiments were asked to judge whether the ten achromatic regions appeared to be under one or two sources of light. When the ten regions were presented as an achromatic luminance continuum [the achromatic version of Fig. 1(d)], 90% of the observers reported one source of illumination. When the ten surfaces were arranged with an apparent illumination edge [the achromatic version of Fig. 1(f)], 90% of the observers reported two sources of light and all but one of them identified the central apparent illumination edge as separating two regions of different illumination.

E. Perceptual Representations and Neural Pathways

Several algorithms have been proposed to estimate illumination and the surface reflectances from a collection of surfaces within a scene.[39,48] These models have representations of the reflecting properties of each surface and also of the regions in space under specific illuminations.[49–53] The results here indicate the complexity of the link between the reflectance level of representation and the illumination level of representation.

Our experiments show that the hue and the saturation of what is perceived can depend on where the surfaces are located in space. Zeki's[54–56] attempt to classify "color-coded cells" in cortical area V1 (that is, cells that respond to a predominant wavelength of light reflected from a surface in a complex surround, independently of its color appearance) may depend on the particular properties of the complex surround used. Zeki's initial classification of such surfaces as "void colors" may lead to confusion on this issue. Void colors, by definition, lack a complex surround. They are not equivalent to a hue–saturation categorization that is typically proposed to study "unattributed color"[31,57] or surface color.[58] In our experiments hue and saturation judgments are made in the context of a spatially complex surround. Surfaces embedded in complex surrounds may be particularly useful for understanding the responses of cells in V1.

Apparent illumination differences may be created by a physical stimulus that does not, in fact, result from two or more real illuminants. Apparent illumination, like apparent motion, is in one sense a perceptual "mistake"[59] in that it allows the visual system to operate as if a scene has illumination differences when none may exist. An open question is whether the neural mechanisms that underlie apparent differences in illumination can accurately represent real differences in illumination. It is clear, however, that grouping regions under a common illumination while simultaneously determining the surface colors within those regions is an important process in natural viewing. The results here support the view that this grouping can change with simple spatial rearrangements of a small, fixed set of stimuli. Full understanding of the neurophysiological substrate that mediates color perception in complex scenes requires physiological experiments that use carefully controlled, moderately complex visual stimuli.

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