

Three-dimensional spatial grouping affects estimates of the illuminant

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The brightnesses (i.e., perceived luminance) of surfaces within a three-dimensional scene are contingent on both the luminances and the spatial arrangement of the surfaces. Observers viewed a CRT through a haploscope that presented simulated achromatic surfaces in three dimensions. They set a test patch to be ~33% more intense than a comparison patch to match the comparison patch in brightness, which is consistent with viewing a real scene with a simple lighting interpretation from which to estimate a different level of illumination in each depth plane. Randomly positioning each surface in either depth plane minimized any simple lighting interpretation, concomitantly reducing brightness differences to ~8.5%, although the immediate surrounds of the test and comparison patches continued to differ by a 5:1 luminance ratio. © 2003 Optical Society of America

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1. INTRODUCTION

The brightnesses (i.e., perceived luminance) of surfaces within a three-dimensional scene are contingent on their spatial arrangement. Gogel and Mershon's¹ adjacency principle states that brightness differences decrease between surfaces of different reflectance as their differences in perceived depth and frontoparallel separation increase. They claim that frontoparallel separation reduces lateral inhibition, which is strongest for surfaces that share a common depth plane.¹⁻⁴ Thus discrepancies in brightness between surfaces of different reflectance within a uniformly illuminated space can indicate the extent of opponent-process activity.⁵

Altering the perceived location of surfaces in more complex three-dimensional scenes can also alter their lightness (i.e., perceived reflectance). Gilchrist⁶ complemented Gogel and Mershon's¹ adjacency principle with a coplanar ratio hypothesis as the principal determinant of the lightness of a given surface. He hypothesized that lightness depends primarily on judgments about adjacent surfaces' reflectance ratios that share a common depth plane. This is because a single depth plane often contains only a single illuminant, whereas the amount of illumination within a volume of space often varies with depth.⁷

A replication of Gilchrist's "real rooms" study, using a CRT and a haploscope, demonstrated in stereovision that the lightnesses of surfaces indeed follow a coplanar ratio hypothesis but that the brightnesses of these surfaces covary with the level of estimated illumination at each depth plane.⁸ Thus both lightness and brightness are affected by more than the luminances of the judged surfaces in that they also can be influenced by the luminances and location in depth of surrounding surfaces.⁵⁻⁹ This suggests that carefully constructed three-dimensional scenes that have a simple lighting interpretation can produce near-perfect lightness constancy,^{6,8} with brightness judg-

ments that covary with the estimated level of illumination.^{7,8,10}

In the current study, observers viewed a CRT through a haploscope that presented simulated achromatic, retinally nonadjacent surfaces in near and far depth planes.⁷ When the luminances of the surfaces in the far depth plane were identical and were one fifth of the luminances of the surfaces in the near depth plane [Fig. 1(a)], the far-depth-plane test patch differed from the near-depth-plane comparison patch in brightness by ~35%. Two different conditions altered the luminances of the surfaces in each depth plane but retained the same coplanar space-average luminance [Figs. 1(b) and 1(c)]. This increased the brightness difference between the test patch and the comparison patch to ~55%.

The above brightness difference is consistent with what an observer would have perceived had the luminances of the surfaces varied in this way in a real three-dimensional scene if each depth plane contained a real different level of illumination. Thus we hypothesize that the increase in brightness difference that occurred in the above conditions was the result of enhancing the likelihood that these stimuli would contain a simple lighting interpretation from which to estimate a different level of illumination in each depth plane. We verified this hypothesis by randomly positioning each surface in the array in either of the two depth planes. In the real world, such reorganization would minimize a simple lighting interpretation. It had a comparable effect here in that it reduced brightness differences to a mere 8.5%, although the immediate surrounds of the test and comparison patches continued to differ by a 5:1 luminance ratio.

We claim that the small brightness difference remained because lower-level simultaneous contrast mechanisms emerged as the likelihood decreased that the scene would contain an unambiguous lighting interpretation from which to estimate different levels of illumination.¹⁰⁻¹⁵

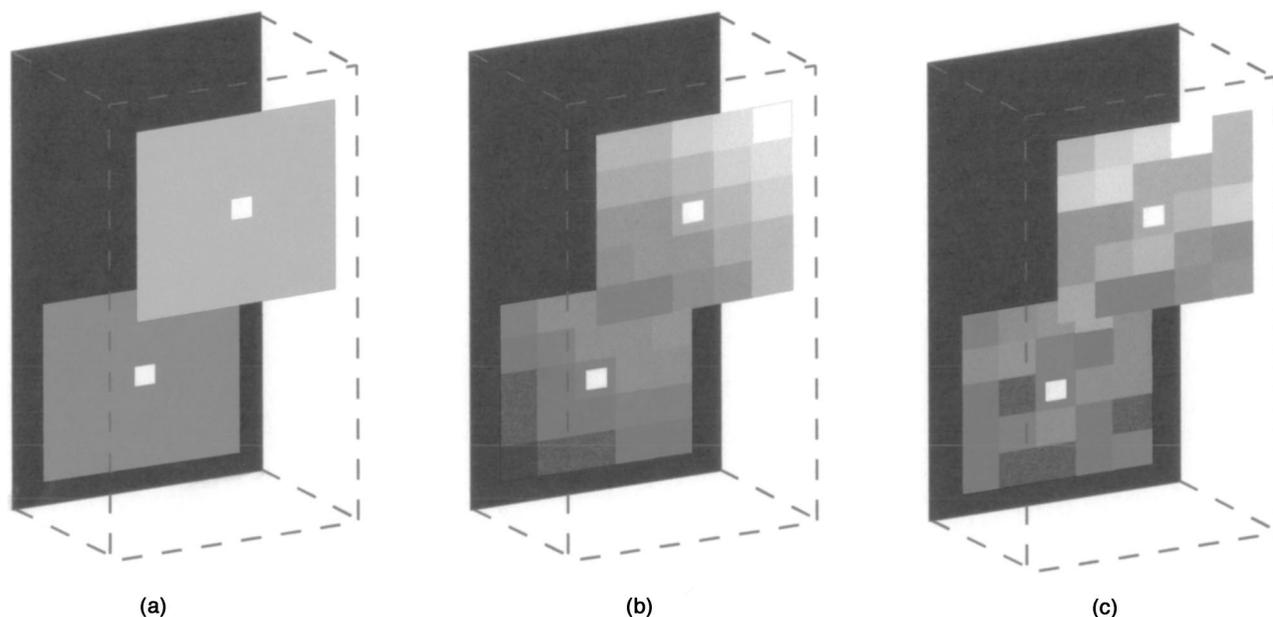


Fig. 1. Schematic of perceived fused CRT images: (a) Simultaneous contrast display. Near (upper field) comparison surround and far (lower field) test surround. Comparison and test patches have identical luminance. (b) Simultaneous-contrast display surrounds divided into 25 1° square patches graded by luminance. Their space-average luminance equals the luminance of the corresponding test and comparison surrounds in (a). (c) Simultaneous-contrast display surrounds with 25 randomly mixed 1° square patches graded by luminance. Their space-average luminance equals the luminance of the corresponding test and comparison surrounds in (a).

The current study uses luminance differences of nonretinal adjacent surfaces in three dimensions to extricate the local contributions to brightness¹² evident in Gogel and Mershon's¹ adjacency principle from Gilchrist's coplanar ratio hypothesis,¹⁶ which requires an estimate of the illuminant.^{11,13,14}

2. METHOD

A. Observers

Four observers with normal or corrected acuity (20/20) and normal stereo acuity were tested. Two paid Wake Forest University undergraduates (AL, a 22-yr-old female and DH, a 22-yr-old male) were inexperienced observers, and naïve regarding the experimental design. The other observers were the authors (KP, a 22-yr-old male, and JS, a 41-yr-old male) and were knowledgeable about the experimental paradigm. JS had prior experience making brightness judgments on complex achromatic displays.

B. Apparatus

Stimuli were generated by a Power Macintosh 7600/132 and presented on an accurately calibrated Radius Press-View 17SR 17-in. color monitor. The 832×624 pixel screen produced achromatic stimuli at CIE chromaticity $x = 0.27$, $y = 0.28$. The scan rate was 75 Hz noninterlaced. The chromaticity of each phosphor was measured spectroradiometrically. The red, green, and blue guns were linearized by use of an 8-bit lookup table. Luminance was approximately constant ($\pm 3\%$) within the central region of the screen that displayed the test and comparison patterns. Observers viewed the monitor through a haploscope at an effective viewing distance of 100 cm in a dark room. They could change the distance of two

small 45-deg mirrors, one in front of each eye, to fuse the left- and right-eye images into a single crisp stereoscopic image.

C. Stimuli

The CRT simultaneously displayed four achromatic patterns on an otherwise dark screen. Identical $5^\circ \times 5^\circ$ patterns (composed of either squares or circles) were located in the upper-left and upper-right quadrants of the screen and contained 34 arc min of crossed retinal disparity. Two other identical $5^\circ \times 5^\circ$ patterns without retinal disparity were located in the lower left and lower right quadrants of the screen. The retinal disparity determined the extent that the upper array projected into a near depth plane compared with the perceived depth plane of the (far) lower array.

Figure 1(a) depicts the appearance of the fused uniform-luminance surface surround, Fig. 1(b) depicts the fused graded-luminance surface surround, and Fig. 1(c) depicts the fused randomly-mixed-luminance surround. In all three conditions the space-average luminance of the surfaces within a depth plane is constant. Figure 1(c) is the condition that most closely replicates the conditions in the study by Schirillo and Shevell.⁷ Used in the first experiment, it produced the maximum brightness differences that observers were able to obtain given two depth planes and constant local induction.¹¹⁻¹⁴

In experiments 1 and 2, each upper and lower array consisted of 25 $1^\circ \times 1^\circ$ diameter patches (either squares or circles). Experiments 3, 4, and 5 used 0.75° diameter circles. The simulated surfaces in each depth plane varied in luminance over a 6:1 range. In the graded and randomly mixed luminance conditions, each surface in the lower test array was set to one fifth (20%) of the luminance of its corresponding surface in the upper com-

parison array. The resulting image, composed of lights covering a 30:1 luminance range, was sufficient for the two arrays to appear to have identical surface reflectances under different levels of illumination.¹⁷

In all experiments, a 0.75° square patch was centered in both arrays. The observer manipulated the lower test patch, and the experimenter set the upper comparison patch to one of seven luminances, presented in pseudo-random order without replacement, using the method of constant stimuli. The comparison luminances were 16.44, 18.79, 21.14, 23.49, 25.84, 28.18, or 30.53 cd/m^2 . All other surfaces of both arrays ranged in luminance from 7.44 cd/m^2 to 31.42 cd/m^2 . The geometric mean luminance across the entire display was 11.43 cd/m^2 . The test patch and the comparison patch were always centered in the middle $1^\circ \times 1^\circ$ region (referred to as the immediate surround) of their respective arrays. In all three surface conditions, the immediate surround of the upper comparison patch had a luminance of 14.55 cd/m^2 and that of the lower test patch had a luminance of 2.91 cd/m^2 .

D. Procedure

Observers did several practice sessions before beginning the reported measurements. They maintained a stable head position with a chin rest. Before each session they dark-adapted for 3 min and then light-adapted for 3 min to a homogeneous field at the luminance level of the geometric mean of the test- and comparison-surround luminances. Observers used a method of adjustment to vary the luminance of the lower test patch to match the upper comparison patch in brightness. They were told to adjust the test patch to appear identical to the comparison patch.^{7,18} They were also told to spend about the same amount of time looking at the upper and lower halves of the display by alternating their gaze between the two halves about once every 2 s. The naïve observers were not told that the two halves of the display differed by a constant. The data show little variability, suggesting that adaptation was stable and complete.

Observers used a computer joystick to match the test-patch luminance in the lower (far) surround to the comparison-patch luminance in the upper (near) surround in either large (2.0 cd/m^2) or fine (0.16 cd/m^2) linear steps. Pressing a button signaled that they made a satisfactory match, at which point the computer recorded their test luminance, and the trial ended. Approximately 2 s later the next trial began. In subsequent trials the initial test luminance was randomly offset $\pm 10\%$ from the previous setting for a given comparison-patch luminance. Within each experimental session, each of the three surface-luminance conditions (i.e., uniform, graded, mixed) was presented in a block. These blocks were randomized across sessions. Thus each of 7 comparison luminances was presented 3 times in 3 conditions, resulting in 63 trials per session. Each of the 5 within-subject design experiments was repeated 3 times, with each session lasting ~ 1 hour. Each data point is the average of 3 separate sessions. Error bars indicate the standard error of the mean across separate sessions.

3. EXPERIMENTS

A. Experiment 1: Brightness Matching with a Square Array

Twenty-five $1^\circ \times 1^\circ$ square, retinally contiguous patches were arranged in each $5^\circ \times 5^\circ$ array. As expected, since every near/far surround (i.e., mixed, graded, or uniform) differed by a 5:1 luminance ratio, observers set the intensity of the test patch below the physical luminance of the comparison patch (Fig. 2). The fact that they decreased the test-patch intensity to make a brightness match indicates that they perceived it to be brighter than the comparison patch.

Observers set the intensity of the test patch lower on the graded-luminance surround [Fig. 1(b)] than on the uniform-luminance surround [Fig. 1(a)]. (In Fig. 2, compare squares with diamonds: AL, $p < 0.05$; DH, $p < 0.01$; JS, $p < 0.01$; KP, $p < 0.01$). This is exactly what would happen if there were a greater real difference in the level of illumination between depth planes in the graded compared with the uniform condition. That is, this is how observers would have set a test patch in shadow that they perceived as brighter than a comparison patch under more illumination that they perceived as dimmer. Although a CRT simulation provides no actual illumination, these findings are consistent with observers having a simple interpretation of a hidden light source in the upper-right corner behind them in the graded condition [Fig. 1(b)], increasing the likelihood that they would estimate that each depth plane contained a different level of illumination.

Three observers judged the brightness of the test patch in the graded-luminance surround condition [Fig. 1(b)] as being roughly equivalent to that in the mixed-luminance surround condition [Fig. 1(c)]. (In Fig. 2, compare circles with squares: AL, $p > 0.45$; DH, $p > 0.20$; KP, $p > 0.40$). Only the most experienced observer, JS, set the test luminance in the mixed-luminance surround condition significantly lower than in the other two surround conditions (JS, $p < 0.01$). Overall, these findings suggest that observers are more likely to estimate greater differences in the level of illumination in scenes containing simple lighting interpretations [i.e., Fig. 1(b) and 1(c)], whereas when specific lighting cues decrease [i.e., Fig. 1(a)],^{7,14} the baseline effects of lower-level mechanisms (e.g., opponent processes) predominate.^{11,12,13,19}

B. Experiment 2: Brightness Matching with a Circular Array

In experiment 1 squares were used to build on prior work done by Schirillo and Shevell.⁷ In experiment 2 a circle of comparable diameter replaced each square, minimizing adjacent borders to only four tangential points, so that when surface size is reduced in experiment 3, concomitantly eliminated border adjacency has minimal impact. Thus each $5^\circ \times 5^\circ$ array now held 25 1° diameter circular patches. The diameter of each circle equaled the width of a square, reducing the total surface area to 79% of the squares. The black background of the screen was visible through the gaps between the circles. The 0.75° square test and comparison patches remained square, though both were centered in the middle 1° diameter circle (rather than square) of their respective arrays.

The results in these conditions (Fig. 3) were similar to those found in experiment 1, even though each circle touched its neighbors at only four points. The average percent deviation from a physical luminance match for the mean of the three conditions' middle data point (i.e., 23.49 cd/m²) for all four observers was ~33%. The test-patch luminance in the uniform-luminance condition remained above that in the graded condition for three of the

observers. (In Fig. 3, compare diamonds with squares: DH, $p < 0.02$; JS, $p < 0.01$; KP, $p < 0.01$; AL showed no significant difference: AL, $p > 0.15$). However, the test-patch luminance in the uniform condition was no longer set significantly above that in the mixed condition for any of the four observers. (In Fig. 3, compare diamonds with circles: AL, $p > 0.45$; DH, $p > 0.30$; JS, $p > 0.20$; KP, $p > 0.25$).

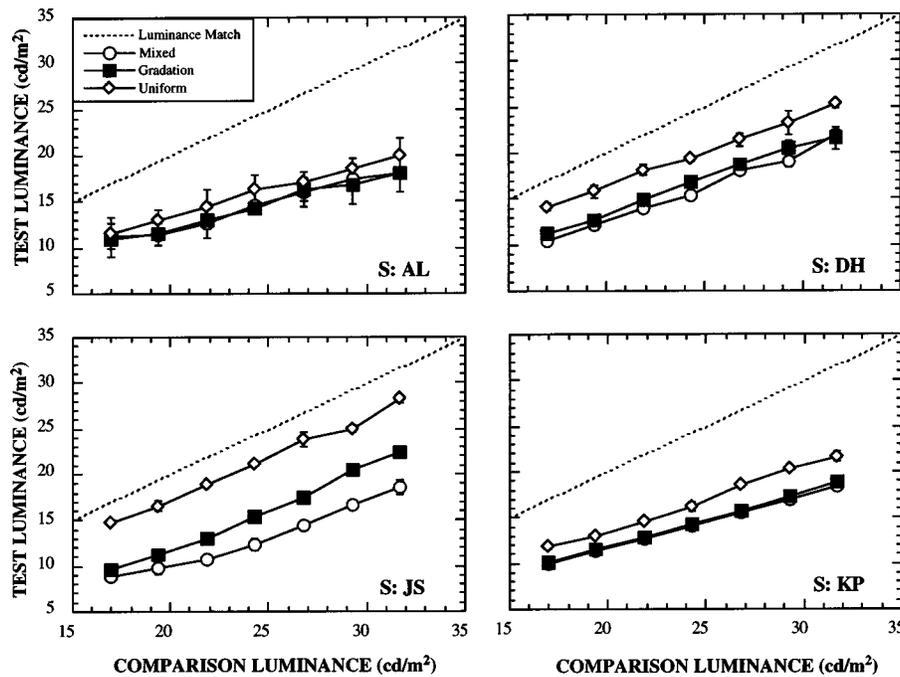


Fig. 2. 1° square-array brightness matches for mixed (circles), graded (squares), and uniform (diamonds) surrounds. Observers: AL, DH, JS, and KP.

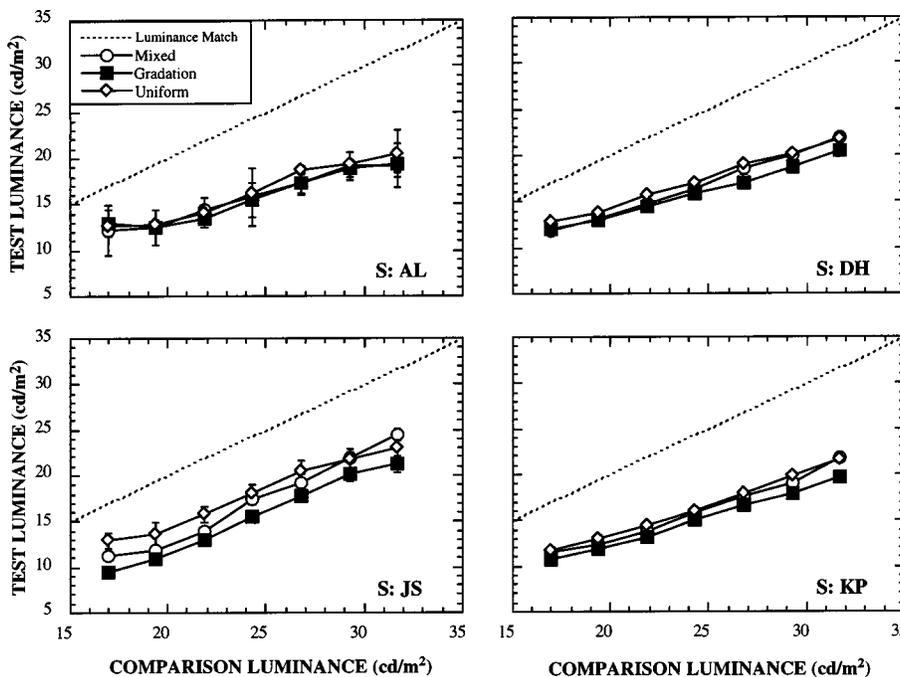


Fig. 3. 1° circular-array brightness matches for mixed (circles), graded (squares), and uniform (diamonds) surrounds. Observers: AL, DH, JS, and KP.

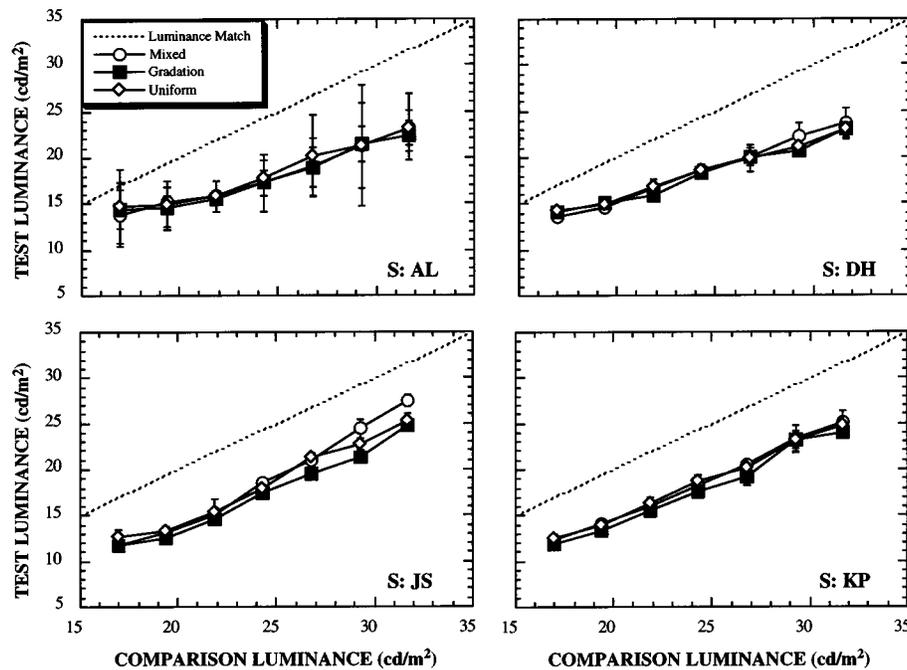


Fig. 4. 0.75° circular-array brightness matches for mixed (circles), graded (squares), and uniform (diamonds) surrounds. Observers: AL, DH, JS, and KP.

C. Experiment 3: Reducing Circle Size Reduces Brightness Differences

The diameter of the circles used in experiment 2 was reduced to 0.75° , leaving the total surface area of the smaller circles $\sim 38\%$ of the surface area of the larger circles. While each circle's diameter was reduced, the spatial location of the center of each circle remained fixed. Thus the circles no longer abutted. The 0.75° square test and comparison patches remained centered within the immediate surrounds of the 1° diameter circle.

The reduction in total area, combined with the elimination of abutting points, substantially reduced the average percent deviation from a physical luminance match to $\sim 22\%$. Moreover, there was no longer a significant difference between the test-patch luminance in the gradient condition and either of the other two luminance conditions with smaller circles. (In Fig. 4, compare squares with either circles or diamonds: AL, $p > 0.50$; DH, $p > 0.46$; JS, $p > 0.19$; KP, $p > 0.20$). As expected from related chromatic experiments²⁰ and the adjacency principle,^{1,2} the frontoparallel separation of the circles reduced local contrast, thereby reducing brightness differences.

D. Experiment 4: Ungrouping Coplanar Surfaces Reduces Brightness Differences

The previous three experiments retained some probability of a simple lighting interpretation by spatially grouping the upper and lower arrays into near and far depth planes, respectively. Experiment 4 minimized such an interpretation by randomly assigning each small circle to a depth plane by using 34 arc min of retinal disparity, so that over the entire field, half of the circles appeared in the near plane and the other half appeared in the far plane (Fig. 5). The test patch and its immediate sur-

round and the comparison patch and its immediate surround remained in their respective far and near depth planes.

Surrounds of either mixed or uniform luminance in this stimulus configuration produced brightness matches that deviated from a physical luminance match by a mere 10% (Fig. 6, open symbols). This finding is consistent with creating stimuli that have highly improbable coplanar lighting interpretations, so that their smaller brightness differences reflect primarily processes driven by local contrast. It is important to realize that these reduced brightness differences occurred despite the fact that the immediate surround of the test and comparison patches remained at a 5:1 luminance ratio. That is, local contrast was the same in this experiment as in the earlier three.

Interestingly, greater brightness differences occurred for the two experienced observers in the graded-luminance surround condition. (In Fig. 6, compare squares with either type of open symbol: JS, $p < 0.01$; KP, $p < 0.01$). This result suggests that the enhanced likelihood of an illumination difference between depth planes derived from a cue that an illumination source is off to the side in the graded-luminance condition may be experience dependent (AL, $p > 0.24$; DH, $p > 0.08$).

E. Experiment 5: Enhanced Brightness Differences with Monocular Viewing

To determine the extent that randomly arranging surfaces of different luminances in stereo depth reduced the likelihood of a simple lighting interpretation, observers in experiment 5 monocularly viewed the same stimuli used in experiment 4. They viewed only one half of the CRT screen through the haploscope by wearing a patch over

the other eye, which eliminated stereo depth. Two of the observers viewed with the left eye, and the other two viewed with the right eye.

Compared with experiment 4, eliminating stereo depth made the test patch appear brighter or the comparison patch appear dimmer or both (Fig. 7, all symbols). That is, the test-patch luminance in all three luminance profiles was set below the physical luminance match by ~22% on average. This suggests that observers are likely to interpret a two-dimensional scene with this configuration of surface luminances as containing more than

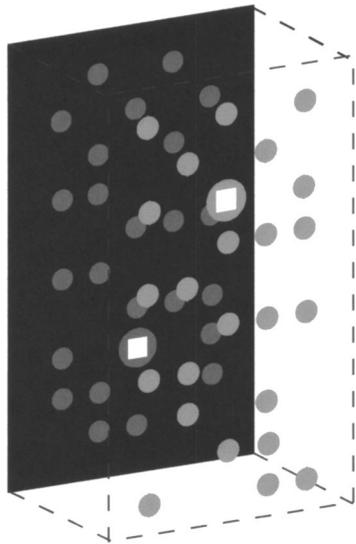


Fig. 5. Schematic of perceived fused CRT image (for clarity, only the uniform surround condition is shown). Each 0.75° diameter circular patch has been randomly assigned a depth plane (except for the 1° square test and comparison surrounds, which remain in the far and near depth planes, respectively).

one illuminant. Strengthening this hypothesis is the fact that observers set the test-patch luminance slightly darker in the graded condition, suggesting an additional shift in their estimation that the test and comparison patches are under different levels of illumination. (In Fig. 7, compare squares with open symbols). Interestingly, simply adding a third dimension can actually make this lighting interpretation less likely. That is, such a scene would now contain a collection of surface luminances in depth that would make it highly improbable that there would be two levels of illumination, one for each depth plane.

4. DISCUSSION

The above findings indicate that brightness matches between test and comparison patches covary with changes in the luminances of surrounding surfaces in a way that is consistent with what a corresponding shift in an estimate of the illuminant would predict. That is, the brightness measurements covaried in the same way as they would in scenes containing different real illuminants.

We found that brightness matches between a test patch in one depth plane and a comparison patch in another depth plane, with a constant 5:1 luminance ratio across depth planes (experiment 1, Fig. 1), were consistent with what observers would have produced had they estimated a different level of illumination in each depth plane.⁶⁻⁸ This effect was largest when the graded luminances of the surfaces within a depth plane were randomized [Fig. 1(c), adapted from Ref. 7]. Subsequent experiments demonstrate the extent to which different spatial luminance arrangements reduce the likelihood of these estimated differences in the level of illumination¹⁴ while maintaining constant local induction.^{12,13} This suggests that bright-

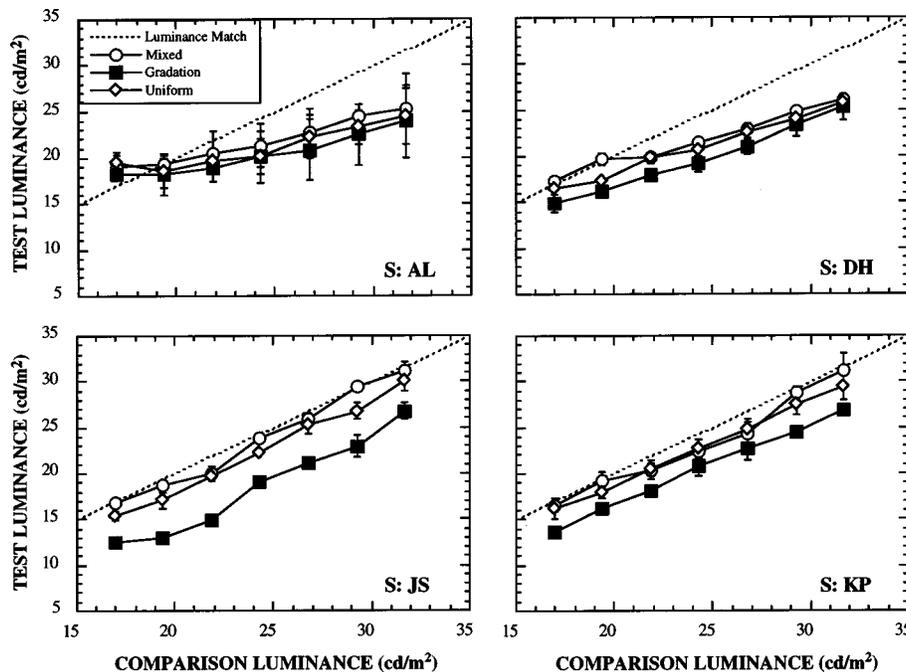


Fig. 6. Brightness matches of 0.75°-diameter circular arrays for mixed (circles), graded (squares), and uniform (diamonds) surrounds randomly assigned to different depth planes. Observers: AL, DH, JS, and KP.

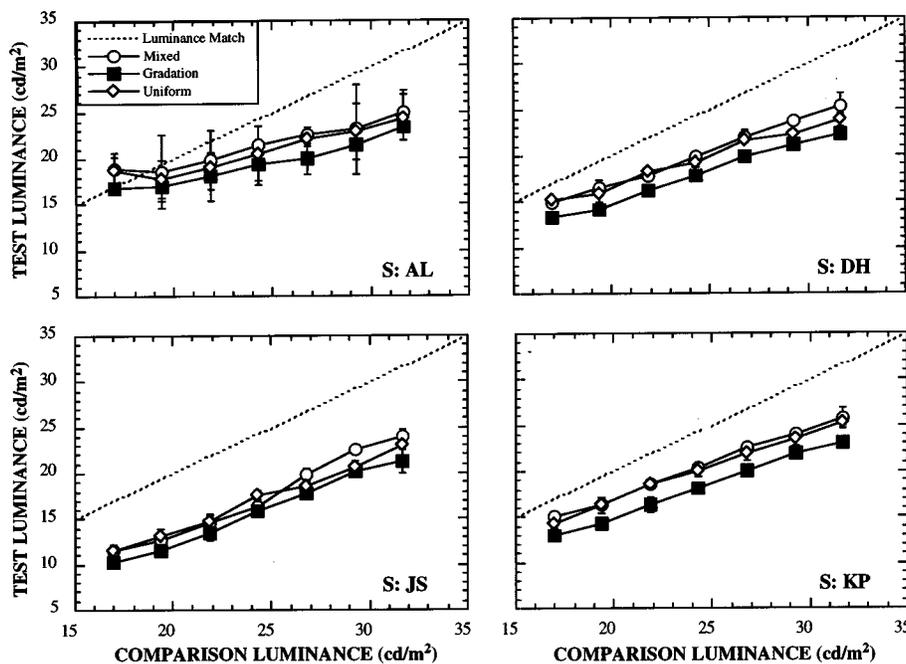


Fig. 7. Brightness matches of 0.75°-diameter circular arrays for mixed (circles), graded (squares), and uniform (diamonds) surrounds randomly assigned to different depth planes under monocular viewing. Observers: AL, DH, JS, and KP.

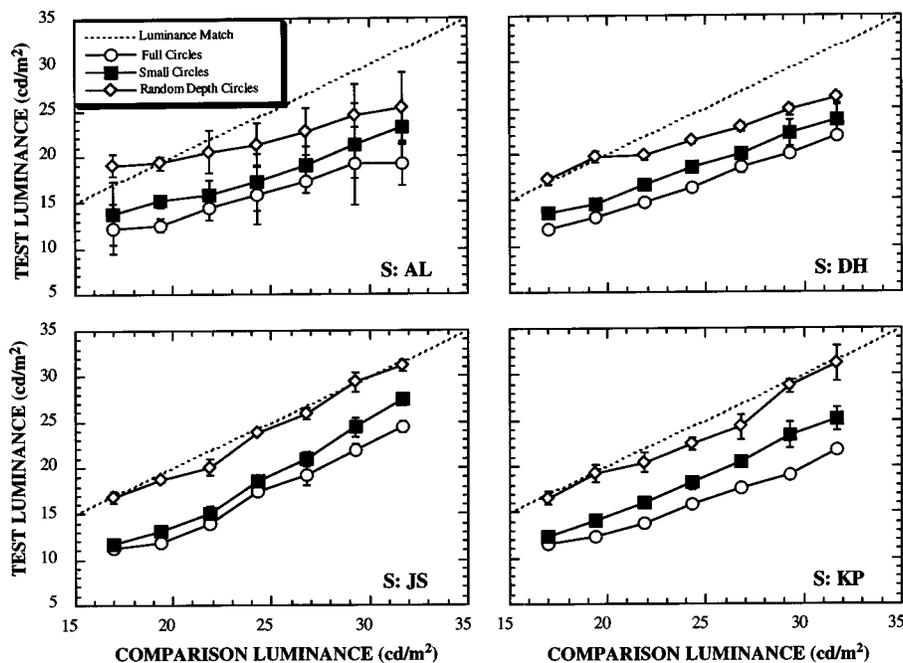


Fig. 8. Only the mixed-luminance-condition brightness matches with 1° diameter circular patches (circles), 0.75° diameter circular patches (squares), and 0.75° diameter circular patches in randomly assigned depth planes (diamonds). Observers: AL, DH, JS, and KP.

ness judgments are the result of multiple mechanisms:¹¹ a local opponent process^{12,13} and a more global process that includes estimating the level of illumination.¹⁴

Many psychophysical studies⁸ use CRTs rather than real papers and lights to simulate surfaces grouped by similar luminance, without any actual illuminant, to create the illusion of regions that differ in illumination. In the current study, using a CRT offered more stimulus control than would have been possible with paper. However,

higher-order processes may limit the degree to which observers accept that a CRT simulation has multiple levels of illumination. Thus, although the current findings are consistent with how brightness differences would increase with an increase in a real difference in the level of illumination, they may underestimate the magnitude of brightness shifts that would be possible in real scenes as observers' estimates of different levels of illumination increase.

Although it is impossible to ensure that observers judged the brightnesses and not the lightnesses of the surfaces in question, the current results are comparable with brightness matches but not lightness matches made in prior related work, where independent judgments of both surface qualities were made.⁷ That is, when a scene promoted a simple lighting interpretation that each depth plane contained a different level of illumination, lightness matches approximated reflectance matches. Unfortunately, the present design cannot reaffirm these notions, since collecting lightness measurements would require informing observers of differences in illumination. Yet recent evidence by Rutherford and Brainard,²¹ relating lightness judgments to direct measures of perceived illumination, dovetails nicely with our current hypothesis.

Replotting only the mixed-luminance surround conditions across the three main experiments reiterates the significance of our main findings (Fig. 8). The large-circle display produced brightness differences of ~33% (Fig. 8, circles), replicating Schirillo and Shevell results.⁷ This represents what may be the maximum extent that illumination could have been estimated to differ across the depth planes in our displays. As expected, reducing the circle size reduced local contrast and thereby brightness differences to ~25% (Fig. 8, squares), since the total surface area of each circle decreased, and the circles no longer abutted. Randomizing the spatial arrangement of the circles' mixed-luminance distribution in depth reduced brightness differences further to a mere 8.5% (Fig. 8, diamonds), which is consistent with the notion that randomizing retinally nonadjacent circles minimizes the ability to estimate different levels of illumination across a three-dimensional image. This becomes evident when viewing the display with one eye covered restores brightness differences to ~17%.

The current stimuli are unique in that darkness surrounded each circle, which suggests that manipulating the estimate of the illuminant need not rely solely on edge integration across the scene.²²⁻²⁴ Recent physiological evidence supports the idea that retinally nonadjacent (i.e., noncontiguous) luminance signals combine in visual cortex, where estimates of illumination probably occur.^{25,26} Thus a plausible model of the above findings would be that local opponent processes produce a relatively small, maybe fixed, amount of possible brightness differences, which can be augmented as the likelihood increases that different levels of illumination are falling on the surfaces being judged.

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