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Articulation: brightness, apparent illumination, and contrast ratios

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Abstract. Luminance edges in the environment can be due to regions that differ in reflectance or in illumination. In three experiments, we varied the spatial organization of 10 achromatic (simulated) surfaces so that some arrangements were consistent with an ecologically valid and parsimonious interpretation of 5 surfaces under two different illuminants. A constant contrast-ratio along a luminance edge in the scene allows this interpretation. The brightness of patches in this condition was compared to their brightness with minimally different spatial arrangements that fail to maintain the constant contrast-ratio criterion. When the spatial arrangement of the 10 surfaces included a luminance edge satisfying the constant contrast-ratio criterion, brightness changed systematically, compared to arrangements without such a luminance edge. We account for the results by positing that a luminance edge with a constant contrast-ratio segments the scene into regions of lower and higher illumination, with the same effect as a difference in real physical illumination: all else equal, a given surface appears brighter under higher than under lower illumination.

1 Introduction

Articulation refers to a Gestalt concept related to scene complexity: the influence of a prevailing illuminant on the perception of surfaces, and its dependence on either the number of surfaces with different luminances or their spatial arrangement (Schirillo 1999a, 1999b). The spatial arrangement of achromatic surfaces is known to affect their brightness, and such changes in the appearance of a fixed luminance have been attributed to *inferences* about the illumination falling on the surfaces (Adelson 1993). An open question is how local luminance differences at edges can result both in inferred global differences in illumination and in perceived local differences in surface appearance (Adelson 1993; Logvinenko 1999).

The following experiments manipulate the arrangement of multiple (simulated) surfaces in a manner designed to segment the scene into regions with different levels of *apparent illumination*. Asymmetric matches reveal how these arrangements affect brightness. In some conditions, the spatial configuration of the surfaces generates a luminance edge between two sets of surfaces, such that the edge can be interpreted parsimoniously to result from a difference in illumination (an *apparent illumination edge*; see Schirillo and Shevell 1997). An apparent illumination edge is a luminance edge that maintains a constant contrast-ratio across it as it traverses a mosaic of surfaces within a scene. In other conditions, the arrangement of the surfaces includes no edge satisfying the constant contrast-ratio condition, resulting in only *apparent reflectance edges* under a single illuminant. In previous work, naïve observers readily perceived these conditions either as two illuminants or a single illuminant, respectively [see table 1 in Schirillo and Shevell (1997)].

In the earlier work, we compared brightness matches in conditions with an apparent illumination edge to matches in conditions that lacked an apparent illumination edge. However, in the latter conditions, we could not evaluate the constant contrast-ratio criterion because each surface abutted only one other surface (figure 1a). Therefore, only a single contrast-ratio along each luminance edge could be determined, and a single value cannot provide evidence of whether the contrast-ratio is varying or constant because there is no other value with which to compare it. Here, we use articulation to examine changes in brightness by introducing violations of the constant contrast-ratio condition, by subtly rearranging the surfaces. If the constant contrast-ratio criterion is required for segmentation into distinct regions of illumination, then minor changes in the spatial arrangement that violate the criterion should yield brightness matches characteristic of only apparent reflectance edges under a single illuminant.

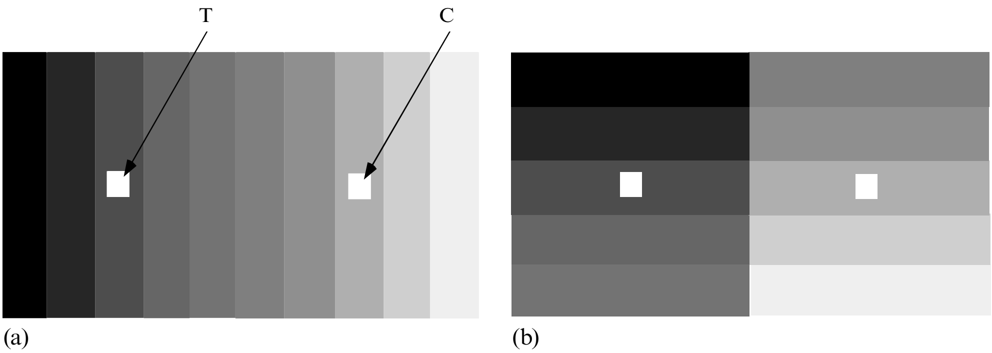


Figure 1. (a) 10 vertical 2.1 deg $\times$ 10.5 deg stripes of increasing luminance from left to right (1.54, 2.19, 3.15, 4.50, 6.45, 9.22, 13.2, 18.9, 27.0, and 38.7 cd m^{-2}). There is no apparent illumination edge. (b) The 10 stripes from (a) with the 5 leftmost stripes rotated 90° clockwise around the test patch T, and the 5 rightmost stripes rotated 90° clockwise around the comparison patch C. The center vertical edge is an apparent illumination edge.

In these experiments, we specifically measure brightness rather than lightness. Although articulation is traditionally defined to account for fluctuations in lightness constancy, we consider brightness matches because brightness correlates with illumination. Lightness, on the other hand, is a correlate of reflectance and ideally is independent of illumination.

2 Method

2.1 *Observers*

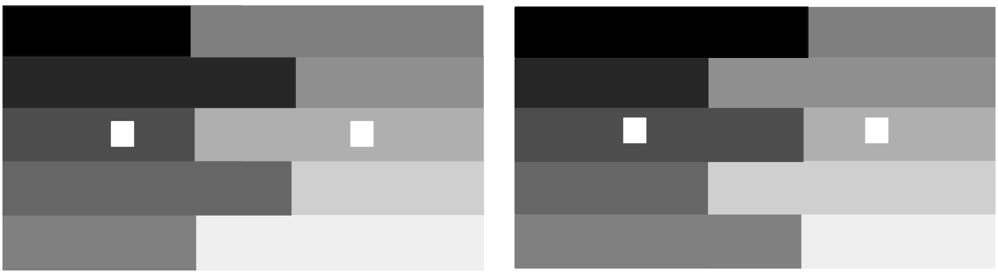
Three observers were tested. All had normal or corrected acuity (20/20). Author JS, a 39-year-old male, was knowledgeable about the experimental design and had prior experience making brightness judgments of surfaces in complex achromatic displays. Observers MN (a 19-year-old female) and AL (a 23-year-old male) were inexperienced observers, and naïve regarding the experimental design.

2.2 *Apparatus*

A Macintosh IIcx computer generated achromatic patterns on an accurately calibrated Nanao T560i 17-inch color monitor. The stimuli were displayed on a 832×624 pixels screen at CIE chromaticity $x = 0.27$, $y = 0.28$. The scan rate was 75 Hz noninterlaced. The chromaticity of each phosphor was measured spectroradiometrically. For linearization of the red, green, and blue guns we used an 8-bit lookup table. The luminance set by the software did not vary appreciably over the effective viewing area. Luminance was approximately constant ($\pm 3\%$) within the central region of the screen that displayed the test and comparison patterns.

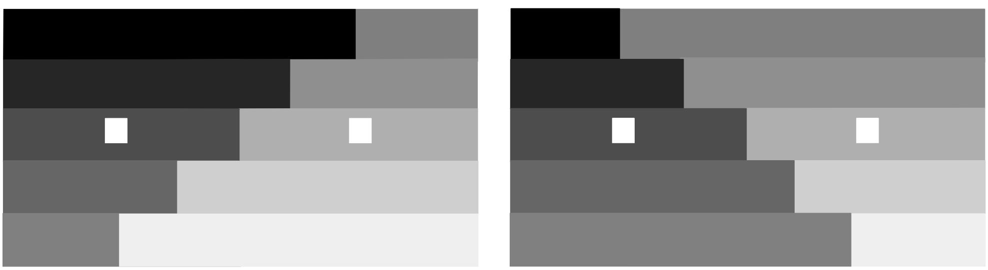
2.3 *Stimuli*

Observers viewed the monitor at a distance of 67 cm in a dark room. The CRT displayed the achromatic patterns on an otherwise dark screen. In experiment 1, the stimuli were composed of 10 stripes of geometrically increasing luminance (see figure 1 caption for the luminance levels); each stripe was a 2.1 deg $\times$ 10.5 deg rectangle. As shown by Schirillo and Shevell (1997), presenting the stripes vertically in order of increasing luminance results in only perceived reflectance edges under a single illuminant, while presenting them in two columns of 5 horizontal stripes gives rise to an apparent illumination edge between the columns (figures 1a and 1b, respectively). Along the apparent illumination edge at the center of figure 1b, the local contrast-ratio is 6 : 1. Experiment 1 shows baseline results reported previously (Schirillo and Shevell 1997). In experiment 2, the stimuli were either the previous 10 horizontal stripes (figure 1b), or the rows were staggered thereby creating a jagged edge, which is inconsistent with the constant contrast-ratio criterion and thus eliminates the parsimonious apparent illumination edge (figures 2a and 2b). In experiment 3, the stimuli were either 10 horizontal stripes staggered in a stair-step fashion (figures 3a and 3b), which is inconsistent with an apparent illumination edge, or 10 stripes with a straight though angled contour, which is consistent with an apparent illumination edge (figures 3c and 3d).

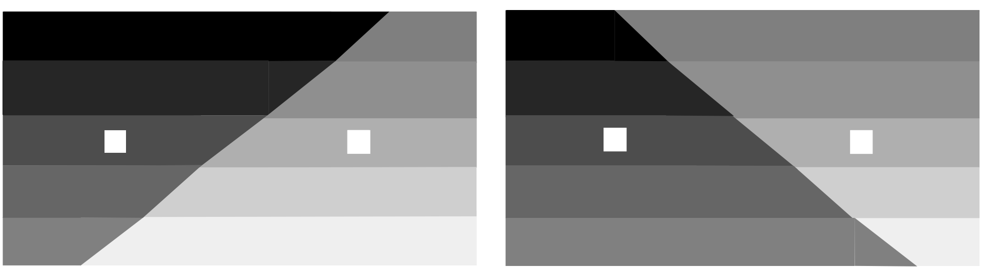


(a) (b)

Figure 2. (a and b) The 10 horizontal stripes from figure 1b are extended or shortened to create a jagged central luminance edge, which is inconsistent with an apparent illumination edge.



(a) (b)



(c) (d)

Figure 3. (a and b) The 10 horizontal stripes from figure 1b are extended or shortened to create a stair-step central luminance edge, which is inconsistent with an apparent illumination edge. (c and d) The 10 horizontal stripes from figures 3a and 3b are modified to include a straight but angled luminance edge, which is an apparent illumination edge.

In all experiments, the observer adjusted the luminance of a 1.25 deg × 1.25 deg square test patch (T) on the left side of the stimulus to match the brightness of one of several incremental or decremental 1.25 deg × 1.25 deg square comparison patches (C) on the right side of the stimulus. They did this by using a joystick to vary the luminance of test T in either large (2.0 cd m^{-2}) or fine (0.16 cd m^{-2}) linear steps. The observer used a button press to switch the step size. Pressing another button signaled the achievement of a satisfactory match, and for the computer to record the luminance of the test patch and end the trial. The computer varied the luminance of the comparison patch from trial to trial in random order, within a range from 5.9 to 59 cd m^{-2} over 10 steps. Between trials, the test and comparison patches returned to the luminance level of their immediate surround for 3 s. Then the next trial began. Each session took about 1 h.

2.4 *Procedure*

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 3 min and then light-adapted for 3 min to a uniform field at the luminance level of the geometric mean of the test-surround and comparison-surround luminances (7.72 cd m^{-2}). Presentations of the stimuli described above then followed.

No more than two experimental conditions were embedded within a single session. Three repetitions of each comparison-patch luminance occurred in each condition. The mean of these three repetitions within a session constituted a measurement for that session. Means and standard errors shown in plots were computed from the repeated measurements from three separate sessions. At most, two sessions were run daily.

Observers used a method of adjustment to vary the luminance of the achromatic test patch (T) to match the brightness of the comparison patch (C). Instructions were to adjust T to appear identical to C in brightness (cf Schirillo and Shevell 1993). Instructions also included a caveat to spend about the same amount of time viewing the right and left halves of the display by alternating one's gaze between the two halves about once every 2 s. Separating the test and comparison patches by 10 deg encouraged eye movements across the center of the display and thereby minimized local adaptation caused by steady fixation. The data show little variability, suggesting that adaptation was stable.

3 Experiments

3.1 *Experiment 1: Vertical apparent illumination edge*

These baseline results were reported previously by Schirillo and Shevell (1997). Observers perceived the 10 vertical stripes in order of increasing luminance from left to right (figure 1a) as 10 stripes of increasing reflectance, all under a single illuminant (Schirillo and Shevell 1997). This is sensible because the overall 39 : 1 luminance range (including test-patch and comparison-patch levels) is well below the 60 : 1 range of black-to-white (lightness) percepts possible under a single illuminant (Jones and Condit 1941; Helson 1943; Evans and Klute 1944).

Fixing the luminances of the stripes immediately surrounding the test and comparison patches preserved local contrast across experiments. Grading the luminances of the other stripes made the geometric space-average luminance of the 5 leftmost stripes identical to the luminance of the single vertical stripe that contained the test patch, and made the geometric space-average luminance of the 5 rightmost stripes identical to the luminance of the single vertical stripe that contained the comparison patch.

To establish an apparent illumination edge between the left and right halves of the stimuli the 5 leftmost stripes were simply rotated clockwise by 90° about the center of the test patch; and the 5 rightmost stripes were rotated clockwise 90° about the center of the comparison patch (figure 1b). The luminances of the stripes within 5 deg of the test patch, and within 5 deg of the comparison patch, were the same in figures 1a and 1b except for rotation, preserving the retinal illumination within 5 deg of each small patch. However, the spatial rearrangement of the stripes in figure 1b produced an apparent illumination edge at the center of the stimulus.

When the luminance of the test patch T was equal to the luminance of the comparison patch C, patch T in figures 1a and 1b appeared brighter than patch C. Observers, therefore, set patch T to a lower luminance to achieve a brightness match. For reference, the upper dashed line in figure 4 is a theoretical equal-luminance match, and the lower dashed-line is a theoretical equal-ratio match (Wallach 1948). The triangles in figure 4 show measurements with no apparent illumination edge (stimulus in figure 1a), and the circles are measurements with an apparent illumination edge (stimulus in figure 1b). All three observers set the luminance of patch T, which was in the region of lower perceived illumination in figure 1b, to a higher luminance when there was an apparent illumination edge, compared to when there was no apparent illumination edge (circles above triangles). Varying the spatial arrangement of the 10 stripes of different luminances can introduce an apparent illumination edge, and affects the brightness of patches on either side of it. We suggest the apparent illumination edge has a grouping effect, making patch T under lower perceived illumination (left patch, figure 1b) appear dimmer, or patch C under higher perceived illumination (right patch, figure 1b) appear brighter (or tpdel

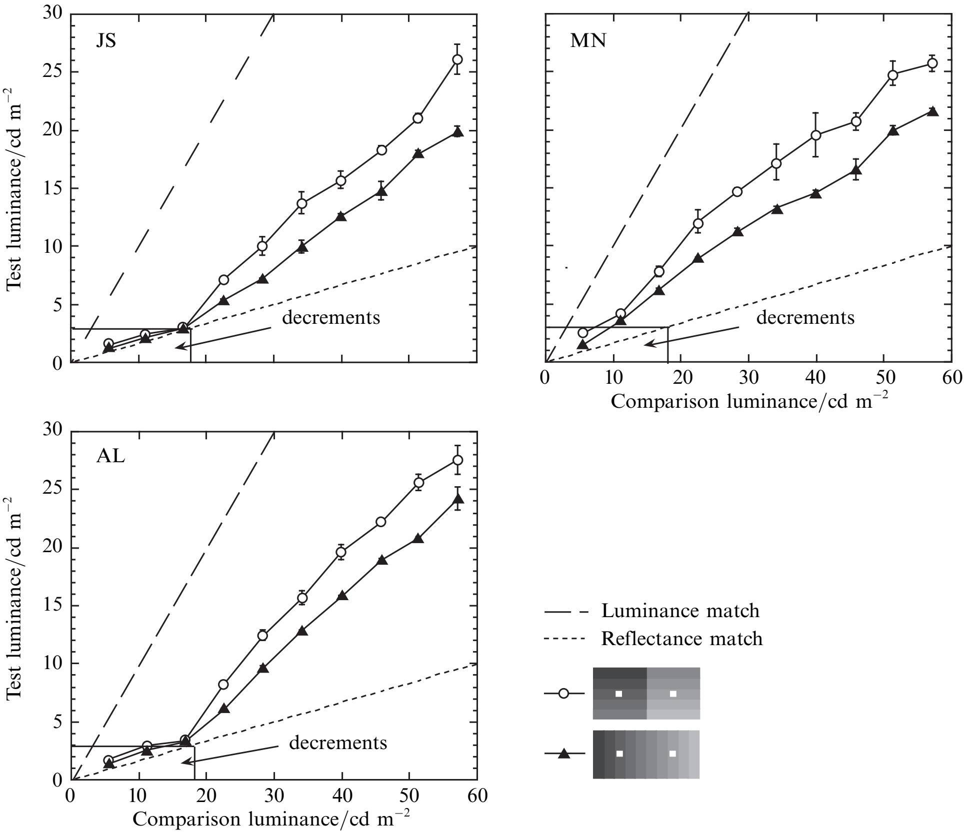


Figure 4. Brightness matches made on horizontal stripes with a vertical apparent illumination edge (circles) or on vertical stripes without an apparent illumination edge (triangles).

both), compared to these same patches presented in figure 1a.

3.2 *Experiment 2: Violating the constant contrast-ratio criterion*
In nature, when an illumination edge extends across the borders of multiple surfaces the contrast ratio across that edge is constant. This is consistent with the stimulus luminance values in figure 1b. To consider whether observers use this constant local contrast-ratio cue to infer that a change in luminance is due to a change in illumination instead of reflectance, we conducted a second experiment with irregular horizontal rows (figures 2a and 2b).

When the horizontal stripes are staggered (figure 2) rather than aligned (figure 1b), observers set the luminance of patch T lower to match a given comparison luminance (figure 5; compare circles to squares-with-slash and squares-with-cross). Thus, the staggered rows have an effect comparable to the 10 vertical graded luminances (figure 1a), both of which are conditions not consistent with an apparent illumination edge. Staggering the horizontal stripes adds contrast ratios along horizontal edges of vertically contiguous stripes that are not at the constant 6 : 1 ratio. We propose that these varying contrast ratios eliminate an apparent illumination edge, and its consequent influence on brightness.

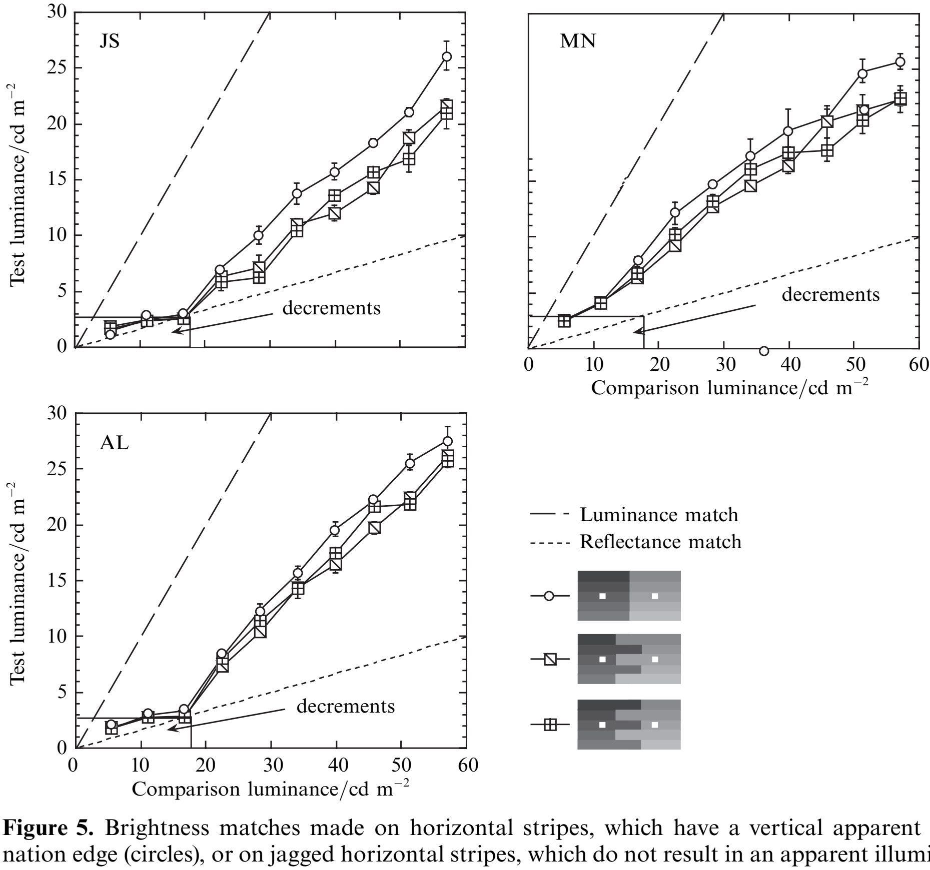


Figure 5. Brightness matches made on horizontal stripes, which have a vertical apparent illumination edge (circles), or on jagged horizontal stripes, which do not result in an apparent illumination edge (squares with either slash or cross).

3.3 *Experiment 3: Nonvertical apparent illumination edge*
The apparent illumination edge in experiment 1 divided the stimulus into two square halves. To insure that the verticality of the apparent illumination edge is not critical to our results, we made additional measurements using a stair-step pattern (figures 3a and 3b). Replacing the stair steps with a straight but slanted contour restored the constant 6 : 1 ratio and thus the apparent illumination edge (figures 3c and 3d).

Observers set the luminance of patch T higher to match a given patch C luminance with the slanted straight edge (figure 6, filled symbols), compared to the stair-step edge (figure 6, open symbols). This is consistent with the stair-step edge not resulting in an apparent illumination edge, with the consequent effect on brightness. On the other hand, a straight but angled luminance edge with a constant contrast-ratio yields an apparent illumination edge and higher test-patch settings.

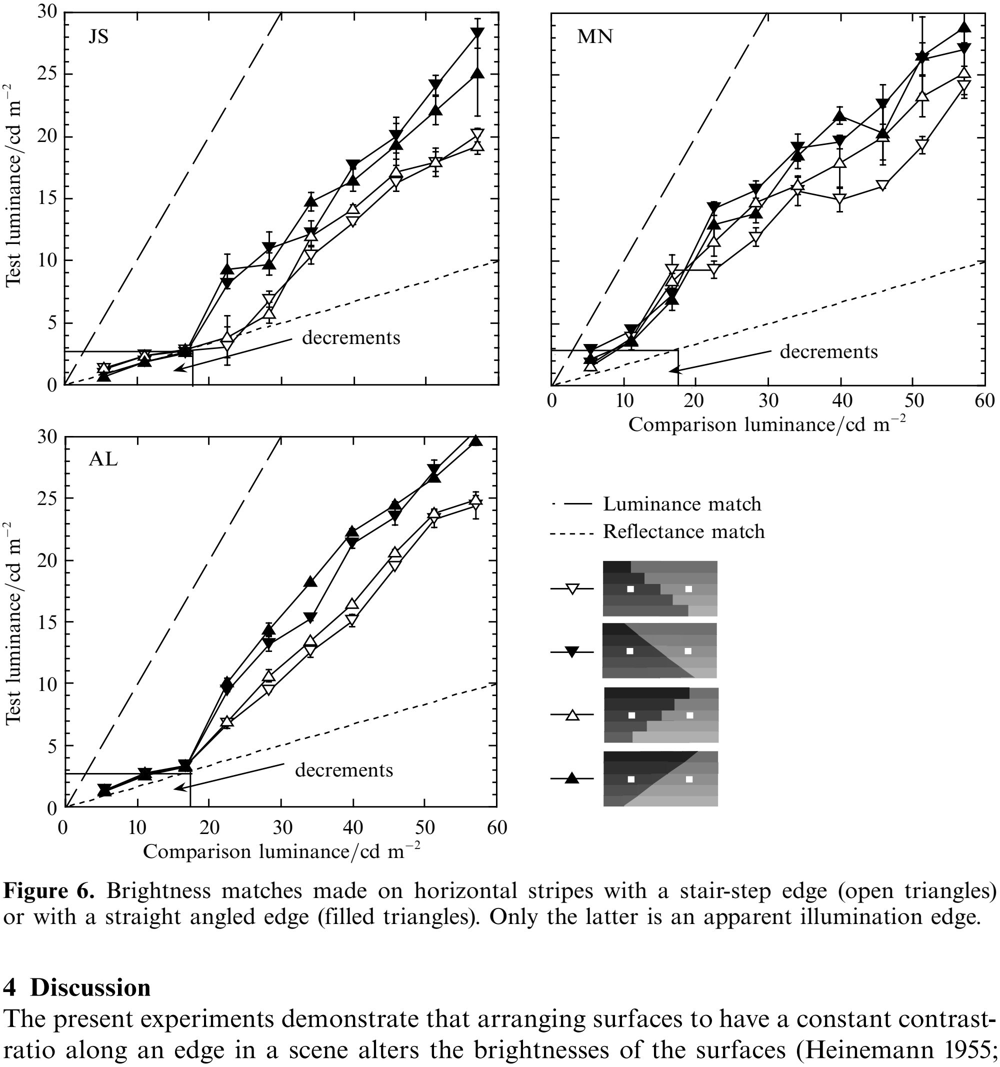


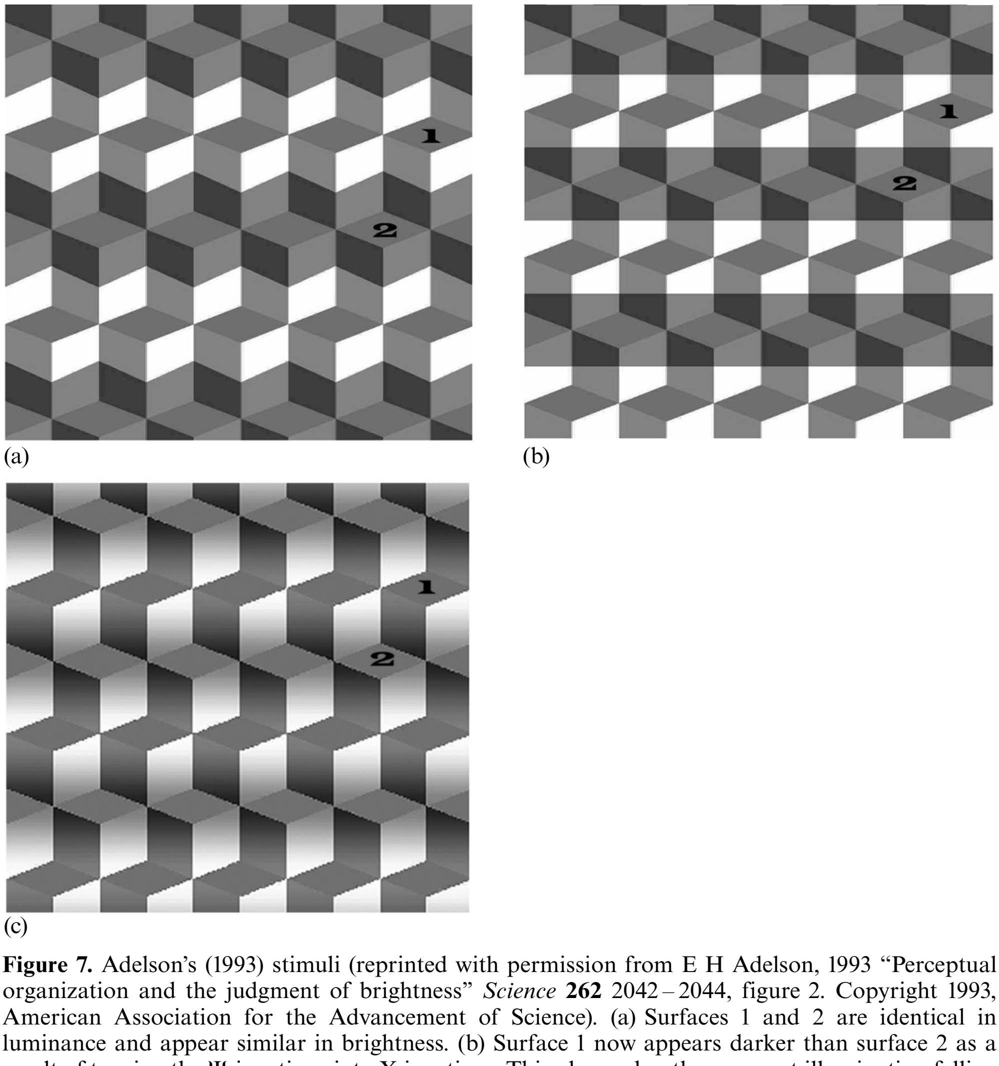
Figure 6. Brightness matches made on horizontal stripes with a stair-step edge (open triangles) or with a straight angled edge (filled triangles). Only the latter is an apparent illumination edge.

4 Discussion

The present experiments demonstrate that arranging surfaces to have a constant contrast-ratio along an edge in a scene alters the brightnesses of the surfaces (Heinemann 1955; Reid and Shapley 1989). We posit that these brightness changes occur for two reasons. First, a constant contrast-ratio is consistent with the retinal stimulation produced by a real change in illumination, causing the visual system to segment 10 surfaces of different luminances into two distinct regions, each region under a different illuminant (Bryngdahl 1966). Second, raising or lowering inferred illumination behaves just as raising or lowering real illumination, which makes a surface appear brighter or dimmer, respectively.

In nature, when any illumination edge, either smooth or jagged, extends across the borders of multiple surfaces, the contrast ratio along the edge is invariant as it passes over the multiple surfaces. In the above stimuli, the apparent illumination edges are ecologically valid in that the contrast ratio across them remains constant. However, with the 'jagged' or 'stair-step' stimuli, the contrast ratio across the jagged or stair-step edge does not remain constant, but rather fluctuates with each 90° turn. Consequently, a change in illumination is not a parsimonious interpretation of the retinal stimulus in these conditions.

One consequence of articulation is that a change in the spatial arrangement of surfaces can alter local contrast ratios. The current study demonstrates that arranging surfaces to contain a luminance edge with a constant contrast-ratio shifts brightness in the direction predicted by a change in a real illuminant. Further, our prior work (see table 1 in Schirillo and Shevell 1997) demonstrated that observers perceive this constant contrast-ratio edge as an apparent illumination edge. These findings, however, only establish a correlation between an apparent illumination edge and changes in brightness. Adelson (1993) also found a relation between inferred illumination and brightness in experiments that manipulated surface-edge junctions (compare figures 7a



(a) (b) (c)

Figure 7. Adelson's (1993) stimuli (reprinted with permission from E H Adelson, 1993 "Perceptual organization and the judgment of brightness" *Science* **262** 2042 – 2044, figure 2. Copyright 1993, American Association for the Advancement of Science). (a) Surfaces 1 and 2 are identical in luminance and appear similar in brightness. (b) Surface 1 now appears darker than surface 2 as a result of turning the Ψ junctions into X junctions. This also makes the apparent illumination falling on surface 1 appear higher than the apparent illumination falling on surface 2. (c) Logvinenko's (1999) stimuli (reprinted with permission from A D Logvinenko, 1999 "Lightness induction revisited" *Perception* **28** 803 – 816, figure 4. Copyright 1999). Surfaces 1 and 2 are identical in luminance; however, surface 1 appears darker than surface 2 as a result of being in a peak of sinusoidal low-frequency modulation, while surface 2 is in a trough.

and 7b). Logvinenko (1999), however, found brightness shifts similar to Adelson's without varying the spatial arrangement of surfaces (and thus not altering edge junctions) by placing surfaces 1 and 2 in the peak and trough, respectively, of low-frequency sinusoidal modulation (figure 7c). This suggests that, while a constant contrast-ratio creates brightness differences between surfaces, it may not be necessary for these surfaces to be perceived to be under different levels of illumination. Future research should explore whether rearranging stimuli to include an apparent illumination edge is sufficient to cause surfaces to differ in brightness.

We suggest that studies of articulation can fruitfully focus on brightness judgments. Historically, the rationale for using highly articulated scenes was to enhance lightness constancy in scenes containing a phenomenological difference in apparent illumination (Gelb 1929/1938; Burzlaff 1931; Henneman 1935; Katona 1935). Future studies of articulation using brightness measures can clarify whether there is a direct relation between contrast ratios, apparent illumination, and brightness; one alternative possibility is that apparent illumination is merely an epiphenomenon.

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References

Adelson E H, 1993 "Perceptual organization and the judgment of brightness" *Science* **262** 2042 – 2044

Bryngdahl O, 1966 "Characteristics of the visual system: Psychophysical measurements of the response to spatial sine-wave stimuli in the photopic region" *Journal of the Optical Society of America* **56** 811 – 821

Burzlaff W, 1931 "Methodological considerations regarding the problem of color constancy" *Zeitschrift für Psychologie* **119** 117 – 235

Evans R M, Klute J, 1944 "Brightness constancy in photographic reproductions" *Journal of the Optical Society of America* **34** 533 – 540

Gelb A, 1929/1938 "Die 'Farbenkonstanz' der Sehdinge", in *Handbuch der normalen und pathologischen Physiologie* Band 12, 1. Hälfte *Receptionsorgane II* Eds W A von Bethe, G von Bergmann, G Embden, A Ellinger (1938, Berlin: Springer) pp 594 – 678 [selection translated in *A Source Book of Gestalt Psychology* Ed. W D Ellis (1938, New York: Harcourt Brace; London: K Paul, Trench, Trubner) pp 196 – 209]

Heinemann E G, 1955 "Simultaneous brightness induction as a function of inducing- and test-field luminances" *Journal of Experimental Psychology* **50** 89 – 96

Helson H, 1943 "Some factors and implications of color constancy" *Journal of the Optical Society of America* **33** 555 – 567

Henneman R H, 1935 "A photometric study of the perception of object color" *Archives of Psychology* **27**(179) 5 – 89

Jones L A, Condit H R, 1941 "The brightness scale of exterior scenes and the computation of correct photographic exposure" *Journal of the Optical Society of America* **31** 651 – 678

Katona G, 1935 "Color-contrast and color-constancy" *Journal of Experimental Psychology* **18** 49 – 63

Logvinenko A D, 1999 "Lightness induction revisited" *Perception* **28** 803 – 816

Reid R C, Shapley R M, 1989 "Non-local effects in the perception of brightness: Psychophysics and neurophysiology", in *Seeing Contour and Colour* Eds J J Kulikowski, C M Dickinson, I J Murray (Oxford: Pergamon Press) pp 324 – 333

Schirillo J A, 1999a "Surround articulation. I. Brightness judgments" *Journal of the Optical Society of America A* **16** 793 – 803

Schirillo J A, 1999b "Surround articulation. II. Lightness judgments" *Journal of the Optical Society of America A* **16** 804 – 811

Schirillo J A, Shevell S K, 1993 "Lightness and brightness judgments of coplanar retinally noncontiguous surfaces" *Journal of the Optical Society of America A* **10** 2442 – 2452

Schirillo J A, Shevell S K, 1997 "An account of brightness in complex scenes based on inferred illumination" *Perception* **26** 507 – 518

Wallach H, 1948 "Brightness constancy and the nature of achromatic colors" *Journal of Experimental Psychology* **38** 310 – 324