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Straightness as a cue for luminance edge interpretation

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In order to determine the reflectance of a surface, it is necessary to discount luminance changes produced by illumination variation, a process that requires the visual system to respond differently to luminance changes that are due to illumination and reflectance. It is known that various cues can be used in this process. By measuring the strength of lightness illusions, we find evidence that straightness is used as a cue: When a boundary is straight rather than curved, it has a greater tendency to be discounted, as if it were an illumination edge. The strongest illusions occur when a boundary has high contrast and has multiple X-junctions that preserve a consistent contrast ratio.

In order to achieve lightness constancy, it is necessary to discount the luminance variations resulting from changes of the illumination falling on a surface, because the luminance is the product of both the reflectance and the illumination. Illumination can vary globally—that is, the overall level can change from time to time—and it can also vary locally in space, as occurs when a shadow is cast on a surface. It is still unclear how the human visual system manages to evaluate illumination changes separately from reflectance changes, since information about the two are mixed in the retinal image. It is generally considered that the visual system uses various cues to distinguish whether a local luminance change should be discounted, as if it were due to illumination, or kept, as if it were due to reflectance (albedo). For example, the soft penumbra of a shadow is a cue that it is caused by illumination rather than pigment. Gilchrist et al. have described this as the problem of edge classification (Gilchrist, Delman, & Jacobsen, 1983). The visual system may not literally classify edges in these terms, but it may instead use a variety of local and global rules for weighing the influence of different luminance variations near and far from a given patch (Adelson, 2000; Blakeslee & McCourt, 1999; Gilchrist et al., 1999; W. D. Ross & Pessoa, 2000). In any case, it is worthwhile asking what factors go into that computation.

Adelson and Somers have recently suggested that the straightness of a border is used as a cue to distinguish whether it is due to illumination or reflectance (Adelson, 2000; Adelson & Somers, 2000, 2001). This notion first arose in considering the "snake" illusion, shown in Figure 1A. The snake pattern contains gray disks on light and dark gray backgrounds; the disks appear to be quite different in luminance even though they are actually identical. The effect is much stronger than in an ordinary simultaneous contrast display (Figure 2). On the other hand, the similar pattern in Figure 1B, comprising the same four patches with the same reflectance as in Figure 1A, produces an effect that is the same as or even weaker than a classical simultaneous contrast. In this article, we propose that the dramatic difference in appearance of the test disks in Figures 1A and 1B is due to the fact that the curves of Figure 1B offer a cue that the borders are due to paint and not shadow, and that the two disks are in the same illumination. In the case of the snake, there are two borders, one curved and one straight, which intersect in X-junctions. The straightness of the contour and the X-junctions it contains are evidence in favor of a change in illumination (or more generally of a change in atmosphere, as would occur when viewing through a dark filter). Thus, the difference in the disks'

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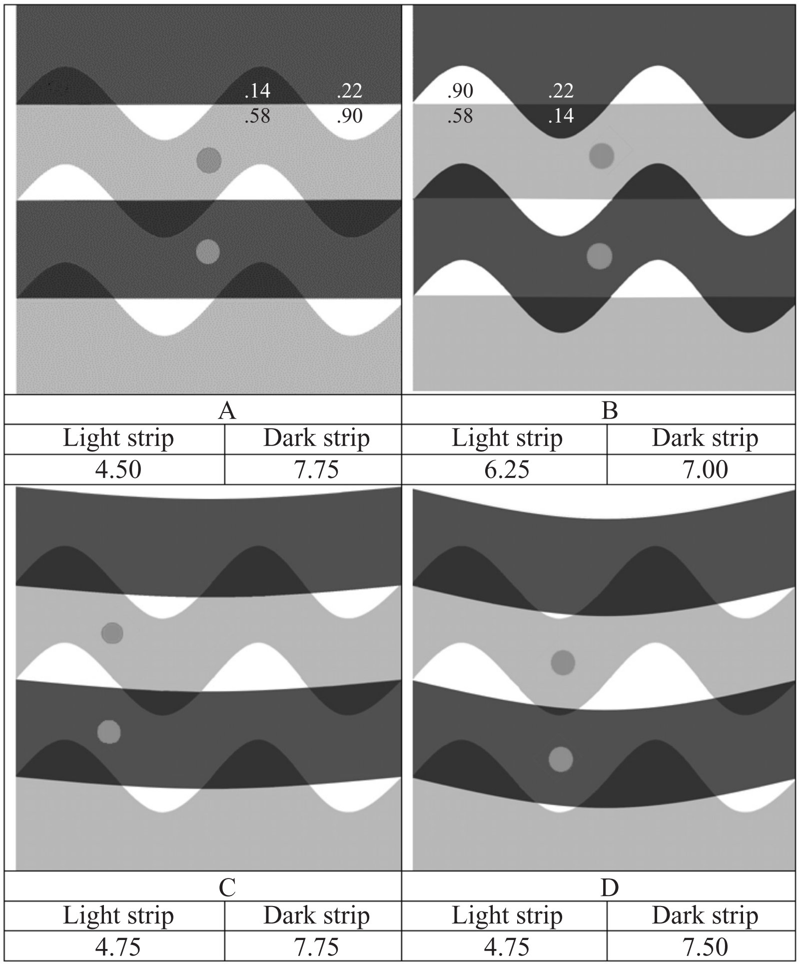


A		B	
Light strip	Dark strip	Light strip	Dark strip
4.50	7.75	6.25	7.00

C		D	
Light strip	Dark strip	Light strip	Dark strip
4.75	7.75	4.75	7.50

Figure 1. Snake patterns with straight (A and B) and bent (C and D) horizontal borders. The numbers present in the patterns show the reflectance of the corresponding patches. The numbers beneath each pattern are the median Munsell matches obtained in the experiment for the test disks (each of which had a reflectance of .43) inserted in the light and dark strips.

lightness in Figure 1A appears to be a result of discounting the luminance change between the horizontal strips.

Here we report on an experiment with this and similar lightness illusions that further corroborates what seems to be a fundamental characteristic of the visual system: For a luminance border to be interpreted as shadow compatible (i.e., produced by a shadow border), it should be straight. Let us consider a variant of the snake illusion, presented in Figures 1C and 1D, in which the luminance border between the horizontal strips is slightly bent. If the disks in Figure 1A, which are physically the same, look rather different because the visual system interprets the luminance border between the horizontal strips as an illumination (shadow) border,[1] then bending the luminance border in Figures 1C and 1D must reduce the likelihood of interpreting it as a shadow border, since, as one can see, the illusion strength in Figures 1C and 1D seems to be reduced as compared to its strength in Figure 1A. The following experiment was undertaken to study quantitatively how the strength of various "snake-like" lightness illusions depends on the geometry of their luminance borders.

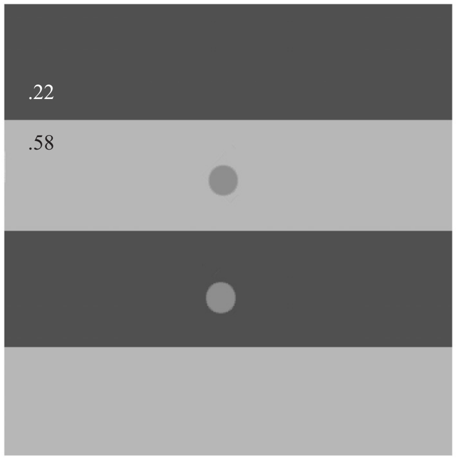
METHOD

Participants

Fifteen observers took part in the experiment. They were not aware of the purpose of the experiment. All of them had normal (or corrected-to-normal) vision.

Procedure

The observers were presented with the 23 patterns reproduced in Figures 1, 2, and 4–8. The patterns were printed on white paper (A4 size) and illuminated by an ordinary tungsten lamp, one at a time. Each picture contained two test objects (either diamonds or disks of the same luminance) inserted in a "light" and a "dark" surround. In one trial, observers were asked to evaluate the lightness of a test object pointed out by the experimenter with a laser pointer. Specifically, observers chose a Munsell chip (the 31-point neutral scale) that they believed matched the test object best. Presentation of pic-



Light strip	Dark strip
5.50	6.75

Figure 2. The control for the patterns in Figures 1, 4, 7, and 8. The pattern comprises strips with the same reflectances as those of the patches into which the test disks are inserted in Figures 1, 4, 7, and 8 (.22 and .58). The numbers at the bottom are the median Munsell matches for the test disks measured in the experiment.

tures and selection of test objects to evaluate were made on a random basis. Five measurements for each test object (in "light" and "dark" surrounds separately) were made. Thus, in all we collected 75 measurements for each test object in each of the two surrounds of each picture.

RESULTS

The Effect of Curvature on the Illusion Strength

The data were analyzed in terms of a histogram of the Munsell matches made by all of the observers for each of the test objects (i.e., inserted into the "light" and "dark" surrounds) for each picture. As an example, the histograms made for the pattern in Figure 1A are presented in Figure 3. As one can see, the two distributions are widely separated. The matches made for the disk in the "light" strip gravitate toward the darker end of the lightness scale, whereas those for the disk in the "dark" strip cluster at the lighter end. Such a shift was evaluated for every picture. If a shift was significant, we claimed that the illusion was observed. We used a nonparametric (Wilcoxon signed rank) test to establish significance because in view of the discreteness of the Munsell scale, we believed nonparametric tests and estimates (e.g., medians rather than means)[2] would be more appropriate. After a statistically significant shift was established (differences at the 5% level were found to be significant for all patterns used in the experiment), we used a shift estimator (Hodges–Lehmann) associated with Wilcoxon's signed rank statistic (Hollander & Wolfe, 1973, p. 33) to evaluate the strength of the illusion.

Note that the Hodges–Lehmann estimator may produce quite different results from the difference of medians (the index that lends itself as the best natural quantitative index of the illusion). For instance, the difference of medians for Figure 1A is 3.25 Munsell units, whereas

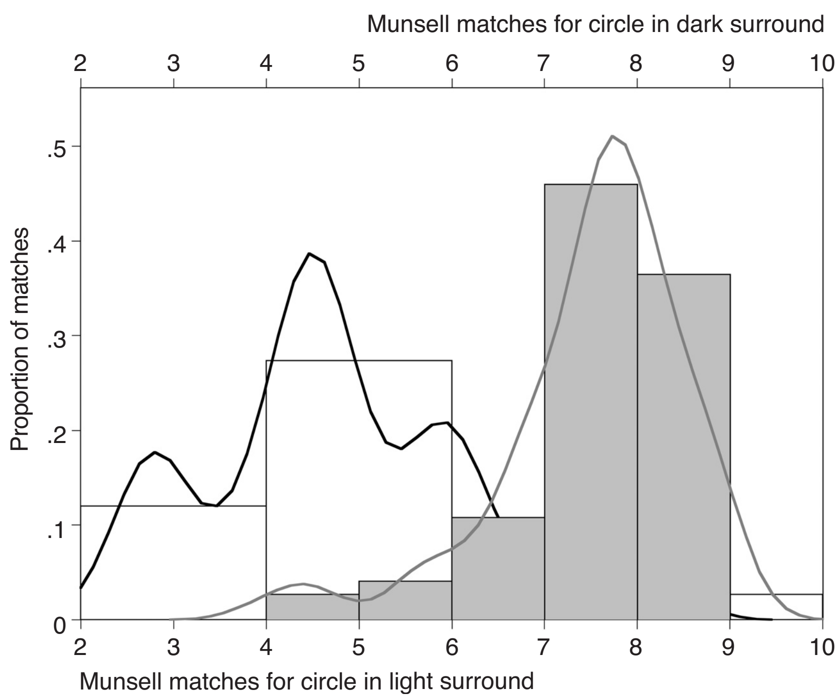


Figure 3. Histograms and density plots (the curves) of Munsell matches obtained for Figure 1A.

Table 1
Median and Mean Munsell Matches for Patterns in Figures 1, 2, and 4

	Light Strip		Dark Strip	
Figure	Median	Mean	Median	Mean
1A	4.50	4.74	7.75	7.51
1B	6.25	5.95	7.00	6.75
1C	4.75	4.92	7.75	7.39
1D	4.75	4.99	7.50	7.23
2	5.50	5.74	6.75	6.58
4A	5.00	5.40	7.25	7.15
4B	6.00	5.94	7.00	6.97
4C	5.75	5.89	7.00	6.99
4D	5.75	5.58	7.00	6.87

Table 2
Lightness Illusion as Measured by Using Different Indexes for Patterns in Figures 1, 2, and 4

Figure	Difference in Medians	Median of Differences	Difference in Means	Hodges–Lehmann Estimator
1A	3.25	3.00	2.77	3.00
1B	0.75	0.50	0.79	0.75
1C	3.00	2.50	2.47	2.625
1D	2.75	2.25	2.24	2.375
2	1.25	0.50	0.84	0.625
4A	2.25	2.00	1.75	1.75
4B	1.00	0.75	1.03	1.00
4C	1.25	1.25	1.10	1.125
4D	1.25	1.25	1.29	1.25

the Hodges–Lehmann estimator was found to be 3.00 Munsell units. As is apparent in Table 2 (as well as in Tables 4 and 6 below), the variance between the median difference and the Hodges–Lehmann estimator may be even larger. The biggest difference was found for Figure 2, for which the Hodges–Lehmann estimator was 0.625 Munsell units, whereas the difference of medians was 1.25 Munsell units.[3]

Figure 2 was used as a control. It was made from Figure 1A by removing the light and dark wavy areas. It shows how much of the illusion observed in Figure 1A can be attributed to the difference in luminance contrast between the disks in the alternating strips and how much to the striped design as such. As Table 2 reveals, Figure 2 produces an illusion strength (0.625 Munsell units) that is very close to the value that the same observers produced for the classical simultaneous lightness contrast display (Logvinenko, 2002a; Logvinenko & D. A. Ross, 2005).

We have tested the pictures in Figure 1 to ascertain if there is a significant difference between the illusions produced by those pictures and the control picture (Figure 2). No significant difference was found for Figure 1B (Wilcoxon signed rank normal statistic with correction $Z = -0.72, p = .47$). As can be seen in Table 2, when the curvature of the luminance border between the strips in Figures 1A, 1C, and 1D progressively increases, the illusion progressively decreases. This decrease of the illusory effect is statistically significant. More specifically, we found a significant difference in the illusion strength for Figures 1A and 1C ($Z = 3.72, p < .01$), as well as for Figures 1C and 1D ($Z = 2.70, p < .01$).

Figures 4A and 4B replicate the main effect found in Figure 1. Figure 4A exhibits quite a strong illusion, whereas the illusion induced by Figure 4B is weak. Moreover, while there was a significant difference ($p < .01$) between the illusion strengths in Figures 4A and 4B,

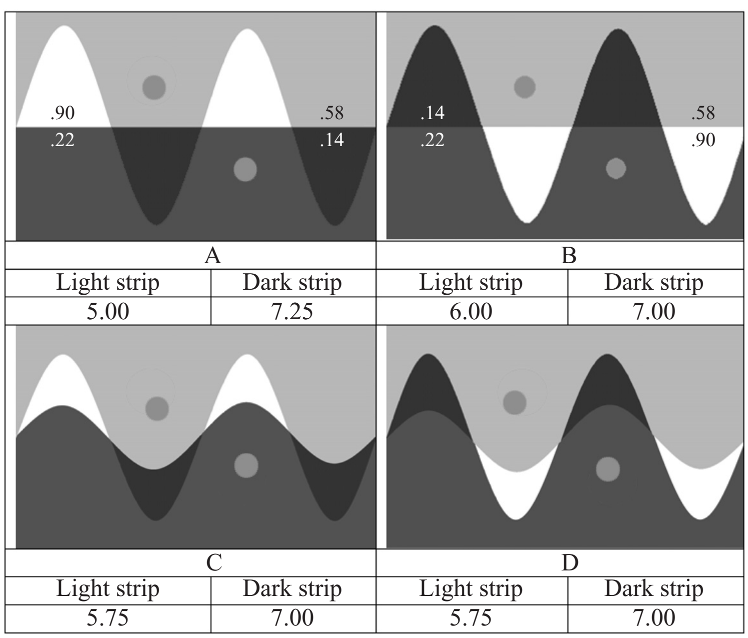
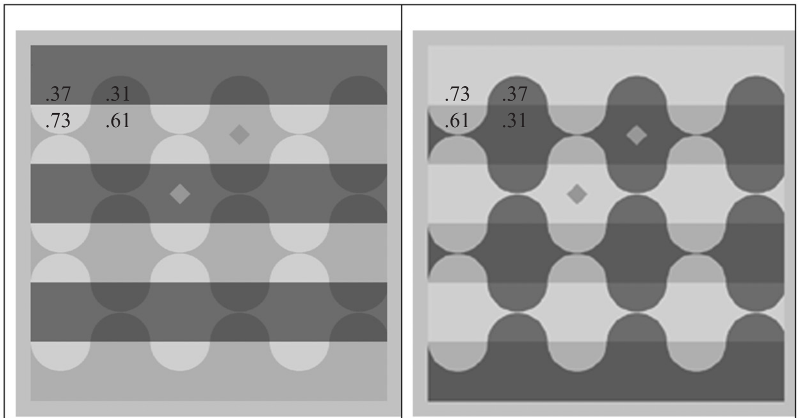
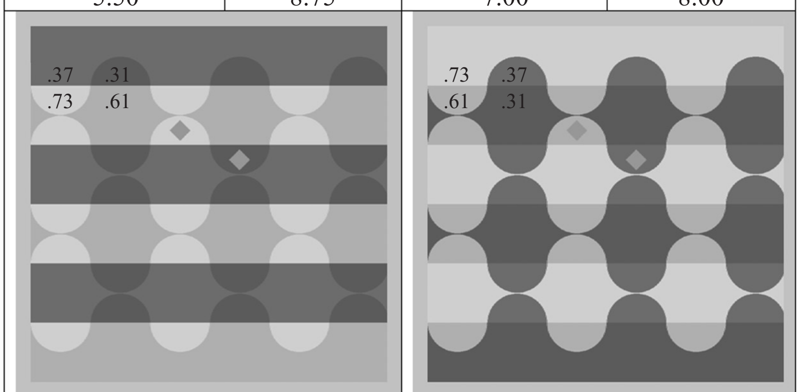


Figure 4. Another "snake-like" set of patterns. When the horizontal straight border in A and B is bent as in C and D, the difference in illusion strength, clearly observed between A and B, disappears for patterns C and D.



A		B	
Light strip	Dark strip	Light strip	Dark strip
5.50	8.75	7.00	8.00



C		D	
Light strip	Dark strip	Light strip	Dark strip
5.50	8.75	7.75	7.75

Figure 5. Another variant of the "snake" patterns. Pattern C differs from A only by position of the test diamonds (which are the same in all four of the patterns, with a reflectance of .52). Patterns B and D are also identical except for the diamond positions. The numbers in the patterns show the reflectance of the patches. The numbers below each pattern are the median Munsell matches for the test diamonds.

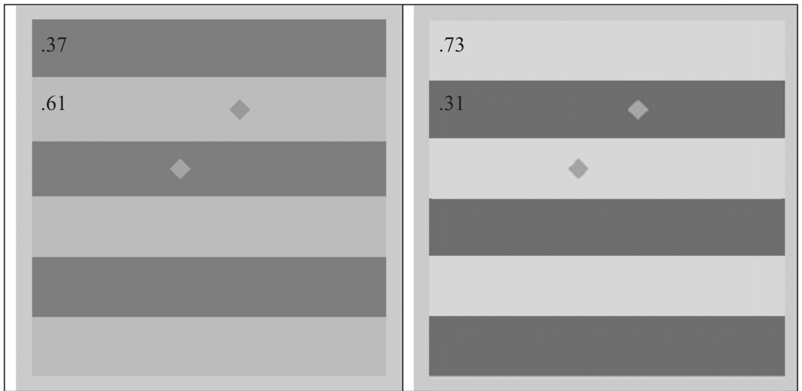
there was no significant difference ($p = .21$) between the illusion strengths in Figure 4B and the control (Figure 2). When the horizontal border in Figures 4A and 4B is bent as in Figures 4C and 4D, the difference in the illusory lightness shift between the two patterns vanishes. To be more exact, there is no significant difference in the illusion strength between Figures 4C and 4D ($p = .07$).

The Effect of Luminance Ratio on the Illusion Strength

Next, two pairs of pictures (Figure 5) show that illusion strength essentially depends on the luminance ratio across the border that the visual system interprets as an illumination border. The controls were patterns 6A and 6B, made from Figures 5A and 5B, respectively, by removing the light and dark wavy areas.

In Figures 5A and 5D, the same diamonds are presented against patches of the same reflectances. Thus, the luminance contrasts of the diamonds against their surround are the same in both pictures. The type of luminance junction at the strip border also is the same in both pictures—it is the double-preserving X-junction that is supposed to indicate that the horizontal luminance borders are produced by an illumination. Therefore, there seems to be every reason to expect an illusion of the same strength for both Figures 5A and 5D. However, as can be seen, the illusion is completely gone in Figure 5D (Table 3). Moreover, the Hodges–Lehmann estimator was found to be negative for Figure 5D (Table 4), which means that on average, our observers saw the diamond in the "dark" surround in Figure 5D as slightly darker (rather than lighter) than the one in the "light" surround.

It should be noted, however, that there is a minor difference between Figures 5A and 5D; namely, the diamonds are located in different areas of the snake. To make sure



A		B	
Light strip	Dark strip	Light strip	Dark strip
6.00	6.50	6.25	7.25

Figure 6. The controls for the patterns in Figures 5A (A) and 5B (B). The reflectance of each strip is shown by the number in it. The numbers at the bottom are the median Munsell matches for the test diamonds.

that this difference does not undermine our conclusion, we also tested Figures 5B and 5C. The patterns in Figures 5A and 5C are the same, as are those in Figures 5B and 5D. The only difference between Figures 5A and 5C (as well as between Figures 5B and 5D) is the position of the test diamonds. As is clear in Tables 3 and 4, the illusion in Figure 5C is almost as strong as that in Figure 5A, whereas it is essentially reduced in Figure 5B. One cannot expect absolutely identical results for Figures 5A and 5C (or for 5B and 5D), since the diamonds in each case have different contrasts with their surrounding patches.

Table 3
Median and Mean Munsell Matches for Patterns in Figures 5 and 6

	Light Strip		Dark Strip	
Figure	Median	Mean	Median	Mean
5A	5.50	5.19	8.75	8.64
5B	7.00	6.85	8.00	7.84
5C	5.50	5.47	8.75	8.71
5D	7.75	7.82	7.75	7.54
6A	6.25	6.21	7.25	7.19
6B	6.00	5.88	6.50	6.42

Table 4
Lightness Illusion as Measured by Using Different Indexes for Patterns in Figures 5 and 6

Figure	Difference in Medians	Median of Differences	Difference in Means	Hodges–Lehmann Estimator
5A	3.25	3.25	3.46	3.50
5B	1.00	1.00	0.99	1.00
5C	3.25	3.25	3.24	3.25
5D	0.00	−0.25	−0.28	−0.25
6A	0.50	0.50	0.54	0.50
6B	1.00	0.75	0.98	0.875

Nevertheless, the similar results for Figures 5A and 5D, on one hand, and for Figures 5B and 5C, on the other, show that the position of the test diamonds has a negligibly small effect.

An essential difference between Figures 5A and 5D (and, likewise, between 5B and 5C) that we believe may be relevant in the present context is that the luminance ratio across the straight luminance border is higher than that across the snake-shaped luminance border. Specifically, the luminance ratio along the horizontal borders between the strips in Figures 5A and 5C is 2.0, whereas it is 1.2 in Figures 5B and 5D. Figures 1A and 1B and Figures 4A and 4B are other pairs of snake pattern variations that feature large differences in the luminance ratio across the horizontal borders. To be more exact, the luminance ratio across the straight luminance borders is 4.1 for Figures 1A and 4A and 1.6 for Figures 1B and 4B. As one can see, the illusion is much stronger for figures in which the luminance ratio is higher (i.e., Figures 1A and 4A). Moreover, as mentioned above, the illusion strength of Figure 1B does not significantly differ from that of the control (Figure 2), which means that the lightness shift in Figure 1B is of the same magnitude as the classical simultaneous lightness contrast effect.

The Effects of Holes and Sharp Edges on the Illusion Strength

The next three pairs of pictures (Figures 7, 8A, and 8B) have been designed to ascertain if patterns topologically equivalent to a ring (i.e., a closed figure with a hole inside) tend to be treated like shadows by the visual system. The control for these patterns was Figure 2.

All eight patterns produced rather low illusory lightness shifts (Tables 5 and 6). Although a significant difference was found between Figures 7C and 7D ($Z = 3.00$,

$p < .01$) and between Figures 8A and 8B ($Z = 3.81$, $p < .01$), it was very small. Therefore, we conclude that these regions with holes are not interpreted in the manner expected of a shadow. This finding is consistent with the notion that in the visual system's interpretation scheme, shadows are less likely to have holes than painted regions are. It should be mentioned, however, that Figures 7, 8A, and 8B contain patterns with sharp angles, which may also reduce the likelihood that these patterns will be interpreted as shadow. For example, although both Figures 8C and 8D contain crooked (nonstraight) luminance borders, sharp angles are available only in Figure 8D. We found no significant difference between Figures 2 and 8D, a finding that corroborates this suggestion.

Table 5
Median and Mean Munsell Matches for Patterns in Figures 7 and 8

Figure	Light Strip Median	Light Strip Mean	Dark Strip Median	Dark Strip Mean
7A	5.75	5.80	7.00	6.94
7B	6.00	5.96	7.00	7.01
7C	5.75	5.75	7.25	7.12
7D	6.25	6.13	7.50	7.30
8A	5.75	5.53	7.25	6.91
8B	5.75	5.81	7.00	6.80
8C	6.00	5.64	7.25	7.11
8D	5.75	5.89	7.00	6.80

DISCUSSION

In these experiments with snake-like figures, we have found that only those figures that contain straight luminance borders with high luminance ratios across them induce strong lightness illusions. Both factors (high luminance ratio and straightness) are important. Neither straightness itself nor high luminance ratio as such is enough to bring about a strong illusion. Indeed, the lu-

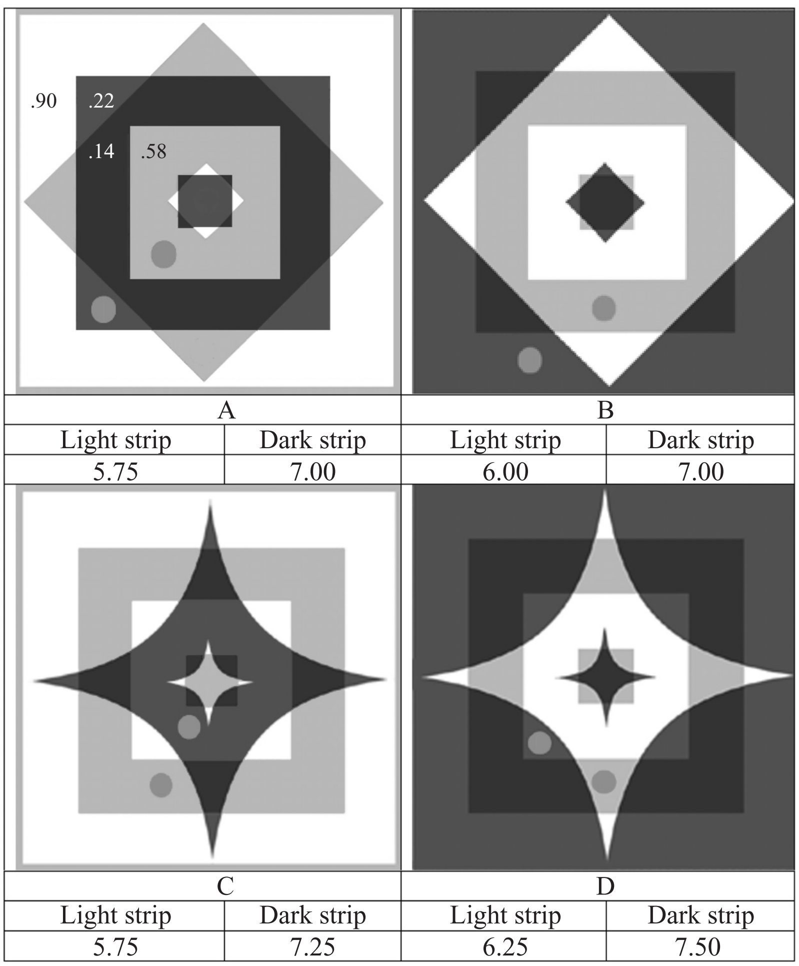


Figure 7. These patterns are constructed from four patches having the same reflectance as those in Figures 1 and 4 (i.e., .14, .22, .58, and .90). The numbers below each pattern are the median Munsell matches for the test disks. See explanation in the text.

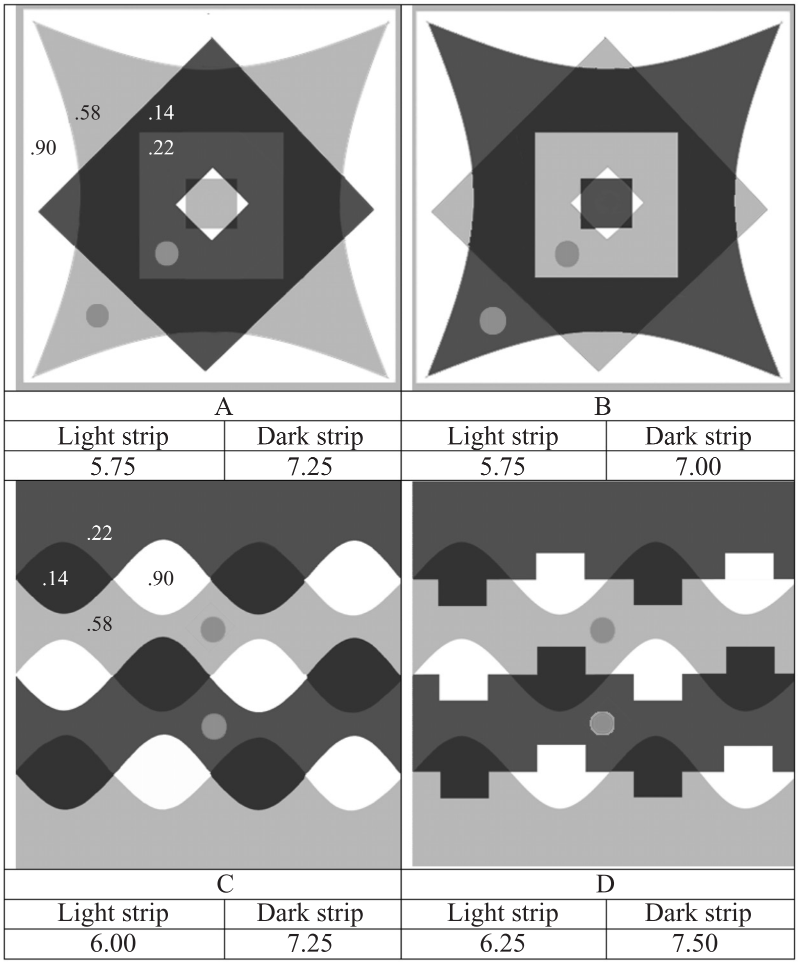


Figure 8. Same as in Figure 7. See explanation in the text.

minance ratio across the snake-shaped luminance borders in Figures 5B and 5D is as high as that across the straight borders in Figures 5A and 5C. Also, the same straight luminance borders (although with a lower luminance ratio across them) are present in Figures 5B and 5D as in Figures 5A and 5C. However, neither Figure 5B nor 5D produces as strong an illusion as Figures 5A and 5C do.

Table 6
Lightness Illusion as Measured by Using Different Indexes for Patterns in Figures 7 and 8

Figure	Difference in Medians	Median Differences	Difference in Means	Hodges–Lehmann Estimator
7A	1.25	1.25	1.14	1.125
7B	1.00	1.00	1.05	1.00
7C	1.50	1.50	1.37	1.375
7D	1.25	1.00	1.17	1.00
8A	1.50	1.25	1.38	1.25
8B	1.25	0.75	0.99	0.875
8C	1.25	1.25	1.47	1.375
8D	1.25	0.75	0.91	0.875

Such a dramatic difference between Figures 5A and 5D (or between Figures 5B and 5C) cannot be accounted for by a low-level theory deriving lightness from local luminance contrast (e.g., Cornsweet, 1970; Hering, 1878/1964; Whittle, 1994a, 1994b), since the diamonds have the same local luminance contrast in both Figures 5A and 5D (and likewise in 5B and 5C). Nor can the difference be accounted for by a mid-level mechanism based purely on the category of luminance junctions, since the junctions are also the same in Figures 5A and 5D and in 5B and 5C. It may be possible to account for these results with more complex systems that take 2D configural properties into account (for example, using approaches that build on W. D. Ross & Pessoa, 2000, or Blakeslee & McCourt, 1999), if these systems are modified to respond appropriately to straight and curved contours. Alternatively, one could also appeal to a Helmholtzian approach.

In order for a Helmholtzian theory to account for these results, however, it would have to be augmented to explain why the "misjudgment of illumination" depends on the detailed geometry of the patterns depicted in Figure 5 (e.g., Logvinenko, 1999; Logvinenko & D. A. Ross, 2005). More specifically, the visual system seems to treat straight sharp luminance borders as illumination (shadow) borders, provided that the luminance ratio across this border is constant. Indeed, if the luminance border is produced by different illuminations, this ratio should be constant; furthermore, it should also equal the ratio of the illuminations' intensities (Logvinenko, 2002b; Marr, 1982). As a matter of fact, the luminance ratio along the horizontal borders between the strips is constant in both Figures 5A and 5D. However, in Figure 5A it is larger (2.0) than in Figure 5D (1.2), and this discrepancy explains the difference in illusion strength between these figures. Indeed, the luminance ratio implies that the illumination of the "light" strips in Figure 5A is two times greater than that of the "dark" ones, whereas the illumination of the "light" and "dark" strips in Figure 5D differs only by a factor of 1.2. Hence, if the visual system perceptually interprets the strips as being differently illuminated, the illusion effect should be, and really is, much smaller for Figure 5D.

It should be noted, however, that there is another luminance border (snake-shaped) in both figures, and along that border the luminance ratio is also constant. In Figure 5A, the luminance ratio along the snake-shaped border is smaller than the ratio in Figure 5D; specifically, the ratios are 1.2 and 2.0, respectively. In other words, both figures are in a sense ambiguous: Both can be interpreted as either a snake-shaped pattern shadowed by a striped pattern, or a striped pattern shadowed by a snake-shaped one. Depending on which pattern is perceptually treated as a shadow, the strength of the illusion will be either high or low. In other words, Figure 5D could produce as strong an illusion as Figure 5A, if the snake-shaped pattern were to be treated as a shadow. However, not one of our 15 observers saw the illusion as more pronounced in Figure 5D than in 5A. It thus follows that in both cases, the visual system prefers to take the striped pattern as a shadow.

To conclude, our data suggest that when the visual system analyzes luminance edges in assessing lightness, it employs an implicit assumption that a straight, sharp luminance border with a constant luminance ratio across it is shadow compatible—that is, produced by an illumination edge. We do not claim, however, that subjects consciously interpret such luminance borders as shadows or as transparent strips at a cognitive level. Most of our observers were not aware of such an interpretation. What we claim is that lightness judgments behave as if the visual system is using straightness as a cue in assessing the degree to which luminance variation should be discounted. This processing may be distinct from the processing that leads to high-level percepts.

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NOTES

1. As a result of this "misjudgment" of illumination, the visual system assigns different lightness to the same luminances (of the test disks). Helmholtz (1867) was probably the first to put forward such an account for lightness illusions of this type (see also, e.g., Adelson & Pentland, 1996; Kingdom, 1997; Logvinenko, 1999).

2. The median and mean Munsell matches are presented in Tables 1, 3, and 5 so that difference between these two estimates can be easily seen.

3. The Hodges–Lehmann estimator is generally not equal to the median of differences between the matches for the "dark" and "light" strips, either. For example, the median of the matches' differences for Figure 2 was found to be 0.5 Munsell units, which differs from both the Hodges–Lehmann estimator (0.625 Munsell units) and the difference of the medians (1.25 Munsell units).

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