A STUDY OF PERCEIVED ILLUMINATION

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We discuss a model of perceived illumination in scenes viewed through a hole. Figure 1 depicts the proximal stimulus corresponding to a circular hole in a screen through which one sees a farther flat two-part background. We assume that the neural signals produced by each single contour of this stimulus activate neural representations of lightness and perceived illumination. This assumption receives support from experimental data (Masin, 1994) and the finding that surfaces and their attributes disappear following the stabilization of the corresponding proximal contours (Krauskopf, 1963). We also assume that the perceived illumination inside the hole results from an integration of the activated neural representations of perceived illumination. This assumption receives general support from studies in the field of information integration theory (Anderson, 1981).

Experimentally, Beck (1959, 1961) has found that judgments of perceived illumination correlate better with average intensity rather than with lower, higher, or total intensity of light reflected by an illuminated surface. From their experimental data, Kozaki (1965, 1973) and Oyama (1968) have similarly concluded that perceived illumination most probably depends on the higher luminance or on some weighted average of the luminances of a scene. Here, we more specifically propose that perceived illumination in a scene viewed through a hole equals a weighted average of the degrees of activation of the corresponding neural representations of perceived illumination, with these degrees being proportional to the luminance differences of the respective contours.

In Figure 1, *S*, *A*, and *B* represent the parts of the proximal stimulus. With reference to this figure, we then propose that

$$i = i_S + w_1 i_{SA} + w_2 i_{SB} + (1 - w_1 - w_2) i_{AB}, \qquad (1)$$

with $\underline{i}$ being the perceived illumination inside the circular hole, i_S the perceived illumination of the screen, w_1 and w_2 weights in the real interval [0,1], and i_{SA}, i_{SB}, and i_{AB} the degrees of activation of the neural representations of perceived illumination relative to the proximal contours between *S* and *A*, *S* and *B*, and *A* and *B*, respectively.

Let *s*, *a*, and *b* be the lightnesses corresponding to *S*, *A*, and *B*, respectively. Because perceived illumination in a scene viewed through a hole varies with $a - s$, $b - s$, or $a - b$ (Katz, 1935) and because neural representations of lightness and perceived illumination should involve the same latest stages of perceptual processing, it seems reasonable that the neural representations of $a - s$, $b - s$, and $a - b$ also are the neural representations of perceived illumination. This possibility and the consideration that lightnesses and degrees of activation of their neural representations should be mathematically identical

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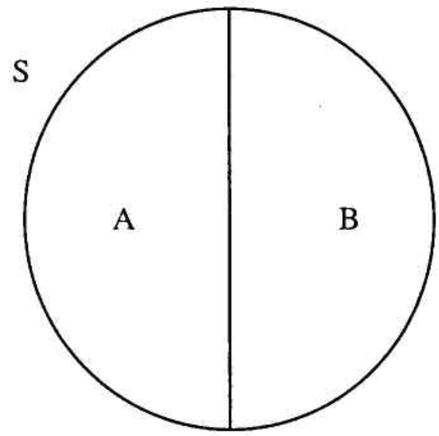

Figure 1.

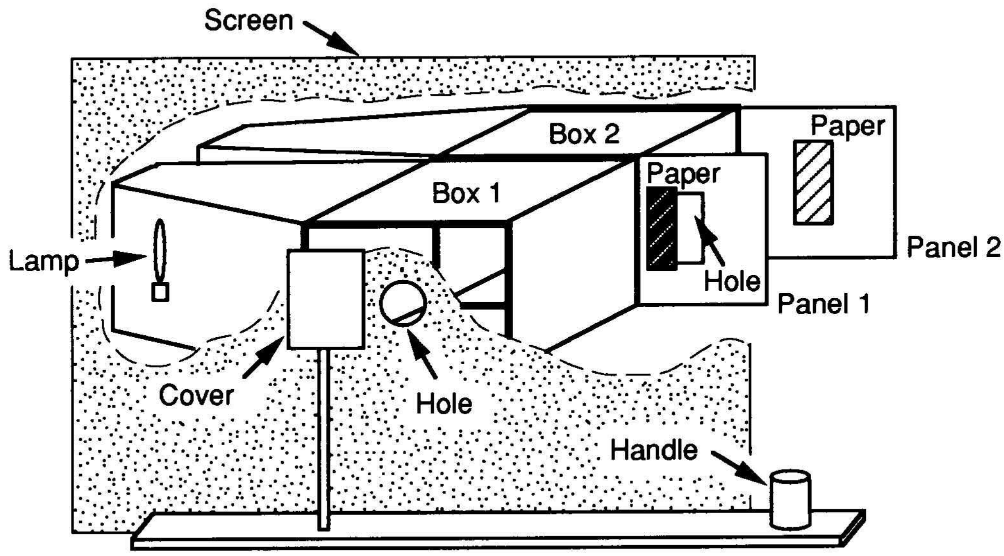

Figure 2.

(Masin, 1993) lead us to hypothesize that $i_{SA} = a - s$, $i_{SB} = b - s$, and $i_{AB} = a - b$. Consequently, we propose that

$$i = i_S + w_1 (a - s) + w_2 (b - s) + (1 - w_1 - w_2) |a - b|. \qquad (2)$$

Here, we consider the case where i, i_S, s, a, and b vary in the same real interval [0, 20].

So that $i = i_S$ when $a = b = s$, the amounts of perceived illumination contributed by $a - s$ and $b - s$ are subtracted from i_S when *A* and *B* are darker than *S*, and are added to i_S when *A* and *B* are lighter than *S*. To encode the finding that perceived illumination increases with lightness (Kozaki & Noguchi, 1976), the amount of perceived illumination contributed by $a - b$ is always added to i_S.

The following experiment quantitatively tested Model 2.

Method

Subjects. Subjects were University of Padua students with declared normal or corrected to normal vision. Each was paid $10 for participating. There were two groups, Group 1 with 20 subjects and Group 2 with 16.

Stimuli for Group 1. With their head on a chinrest, subjects sat in front of a 100 x 60 cm, base by height, frontal-parallel screen. In the middle of this screen there was a circular hole with a radius of 4.8 cm. A movable cover served to hide this hole. Eye distance was 230 cm.

Figure 2 depicts the screen as broken to illustrate that behind there were two adjacent boxes, Boxes 1 and 2. These boxes had the same measures, 28 (base) x 21 (height) x 21 (depth) cm, and no front or back sides. With both eyes, subjects looked inside Box 1 through the circular hole in the screen. Through a vertical slit between Boxes 1 and 2, the experimenter inserted a 30 x 21 cm, base by height, frontal-parallel black slab of masonite (Panel 1). Through another vertical slit near the back of Box 2, the experimenter inserted another frontal-parallel slab of masonite of equal size and color (Panel 2). Figure 2 depicts these panels as partially inserted.

The same figure illustrates that in the middle of Panel 1 there was a 5 x 11 cm, base by height, rectangular hole. With this panel fully inserted, subjects looked into Box 2 through this hole. On the front surface of Panel 1, there was a 5 x 12 cm, base by height, rectangular NCS neutral gray piece of paper placed adjacent to the rectangular hole. On the front surface of Panel 2, there was another 7 x 13 cm, base by height, rectangular NCS neutral gray piece of paper. With both panels fully inserted, this other paper was visible through the rectangular hole in Panel 1 and was positioned so subjects could not see its contour.

We now redefine Figure 1 as the distal stimulus viewed by the subject, where *S* is the screen, *A* the rectangular piece of paper on Panel 1, and *B* the rectangular piece of paper on Panel 2. From the subject's viewpoint, the contour between *A* and *B* was vertical and in the middle of the circular hole. The microstructure of *S*, *A*, and *B* was invisible, and *A* and *B* looked coplanar and a few centimeters behind *S*.

One 9W Osram Dulux S lamp separately illuminated each box. Figure 2 shows the approximate position of one lamp, which was inside one of two equal polyhedrons. The left side of Box 1 was one face of one polyhedron and that of Box 2 one face of the other. These sides were made of white translucent plastic. Internally, both polyhedrons and the right, bottom, and top sides of both boxes were painted white. The back surface of the screen was painted black.

The experiment took place in a dimly lit room, with an illumination level of 0.7 lx where the subject was located. The luminances of both *S* and the cover were 0.001 cd/m^2 (black). The luminances of *A* and *B* were 2.5, 7.5, 35.5, or 63.5 cd/m^2. A photometric test showed that the light reflected by any panel in one box did not appreciably affect that reflected by any of the other panels in the other box.

The presentation of one stimulus was as follows. Initially, the cover hid the circular hole. The experimenter inserted Panels 1 and 2 into their slits, and then displayed the stimulus by moving, with a handle, the cover all the way to the subject's left (Figure 2). After the subject's response, the experimenter moved the cover back to its initial position and changed Panels 1 and 2. A partition (not shown in Figure 2) made all these operations invisible to the subject. There were 16 stimuli, one for each combination of the luminances of the pieces of paper on Panels 1 and 2.

Stimuli for Group 2. The stimuli were the same as those for Group 1, except that the luminances of the cover and front surface of *S* were 0.05 cd/m^2 (dark gray).

Procedure. The procedure for Groups 1 and 2 was the same. It consisted of two parts. In the first part, each subject rated the perceived illumination inside the circular hole. Examples of illuminations in rooms before and after the light was turned off served to define "perceived illumination." To rate, subjects used the integers 0-20, the higher the perceived illumination the larger the integer. The integers 0 and 20 were defined as absence of perceived illumination (complete darkness) and the highest possible illumination ever experienced by subjects in their lives, respectively. The entire set of 16 stimuli was presented twice consecutively, with different random orders for each set and subject. Subjects also rated the perceived illumination of *S* in the proximity of the circular hole, when both luminances in this hole were the highest and when both were the lowest. Half the subjects produced this rating with the highest luminances at the end of the first presentation of the entire set of stimuli, and that with the lowest luminances at the end of the second presentation. For the other half this order was reversed. For familiarization, subjects rated 2-3 stimuli selected at random before starting the experiment.

In the second part, each subject rated the lightnesses of *A* or *B* (that is, *a* or *b*). To rate, subjects again used the integers 0-20. The integers 0 and 20 were now defined as the blackest black and the whitest white ever experienced by subjects in their lives, respectively. The closer a lightness was to the whitest white the closer the integer had to be to 20. The entire set of 16 stimuli was presented four times consecutively, with different random orders for each set and subject. All subjects rated *a* during the first and third presentations of the entire set of stimuli, and *b* during the second and fourth presentations. Subjects also rated the lightness of *S* (that is, *s*) in the proximity of the circular hole, when both luminances in this hole were the highest and when both were the lowest. Half the subjects produced this rating with the highest luminances in the hole at the end of the second presentation of the entire set of stimuli, and that with the lowest luminances at the end of the fourth presentation. For the other half this order was reversed. No stimulus for familiarization was presented before starting the second part of the experiment.

Results and discussion

The means of the two ratings of each subject per stimulus were used as scores in the following statistical analyses. For Group 1, the mean ratings of *s* were 1.0 and 2.5 [statistically different, $t(19) = 3.8$, $p < .01$], and those of the perceived illumination of *S* 1.6 and 3.1 [$t(19) = 2.8$, $p < .05$], for the lowest and highest luminances in the circular hole, respectively. For Group 2, the mean ratings of <u>s</u> were 3.8 and 2.7 [$t(15) = 2.3$, $p < .05$], and those of the perceived illumination of *S* 2.3 and 3.4 [$t(15) = 1.2$, n.s.], for the lowest and highest luminances in the circular hole, respectively. Since the illumination in the experimental room was low and that inside the circular hole relatively strong, a soft halo was visible around this hole. This halo and simultaneous contrast account for the statistical significance of the above differences between mean ratings.

For Groups 1 and 2, Table 1 reports the mean ratings of *a* and *b* and Table 2 those of the perceived illumination inside the circular hole.

In Figure 3, the left diagrams represent the mean ratings of perceived illumination from Groups 1 (top) and 2 (bottom) as a function of the luminance of *B*. The parameters are the luminance of *A*. Two separate 4 x 4 (luminance of *A* x luminance of *B*) analyses of variance showed that the main effects and the interaction were significant ($p < 0.001$) for Group 1, whereas the main effects were significant ($p < 0.0005$) and the interaction nonsignificant [$F(9,126) = 2.09$] for Group 2.

Because w_1 and w_2 are unknown, Model 2 cannot predict the data in Table 2 from the subject's ratings of i_S, *s*, *a* and *b*. However, an indirect test of this model seems possible. The symmetry of stimuli suggests that $a - s$ and $b - s$ were of equal weight. Then, we may predict that a least squares fitting of Model 2 to the data in Table 2 should produce equal estimates of w_1 and w_2.

The procedure for this fitting was as follows. Recall that subjects rated i_S and *s* when both luminances in the hole were the highest and when both were the lowest. Considering the small differences between these ratings, the ratings of i_S and *s* for all the other combinations of luminances were approximately estimated by linear interpolation. Table 3 reports these estimates.

The range of lightnesses (or illuminations) that subjects perceived during the experiment was an unknown part of the range of lightnesses (or illuminations) that subjects perceived in their lives. Consequently, it seems quite likely that the lightnesses and illuminations perceived during the experiment were differently mapped within the common 0-20 response range. However, some linear transformation of *s*, *a*, and *b* – $x\,s + y$, $x\,a + y$, and $x\,b + y$, respectively – should make the lightness and perceived illumination scales comparable.

A computer search procedure found the combinations of *x*, *y*, w_1, and w_2 that minimized the sum of the squared differences between the illumination values computed by Model 2 and the corresponding mean ratings of perceived illuminations in Table 2. A numerical test showed that no combination of parameters other than the following minimized this sum: $x = 1.58$, $y = -7.14$, $w_1 = .40$, and $w_2 = .37$ (Group 1) and $x = .98$, $y = -.69$, $w_1 = .46$, and $w_2 = .45$ (Group 2).

In Figure 3, the right top and bottom diagrams refer to Groups 1 and 2, respectively. Each diagram represents the illumination values computed by Model 2 using the corresponding estimated weights, as a function of the luminance of *B* and with the luminance of *A* as the parameters. As predicted, Model 2 satisfactorily fits

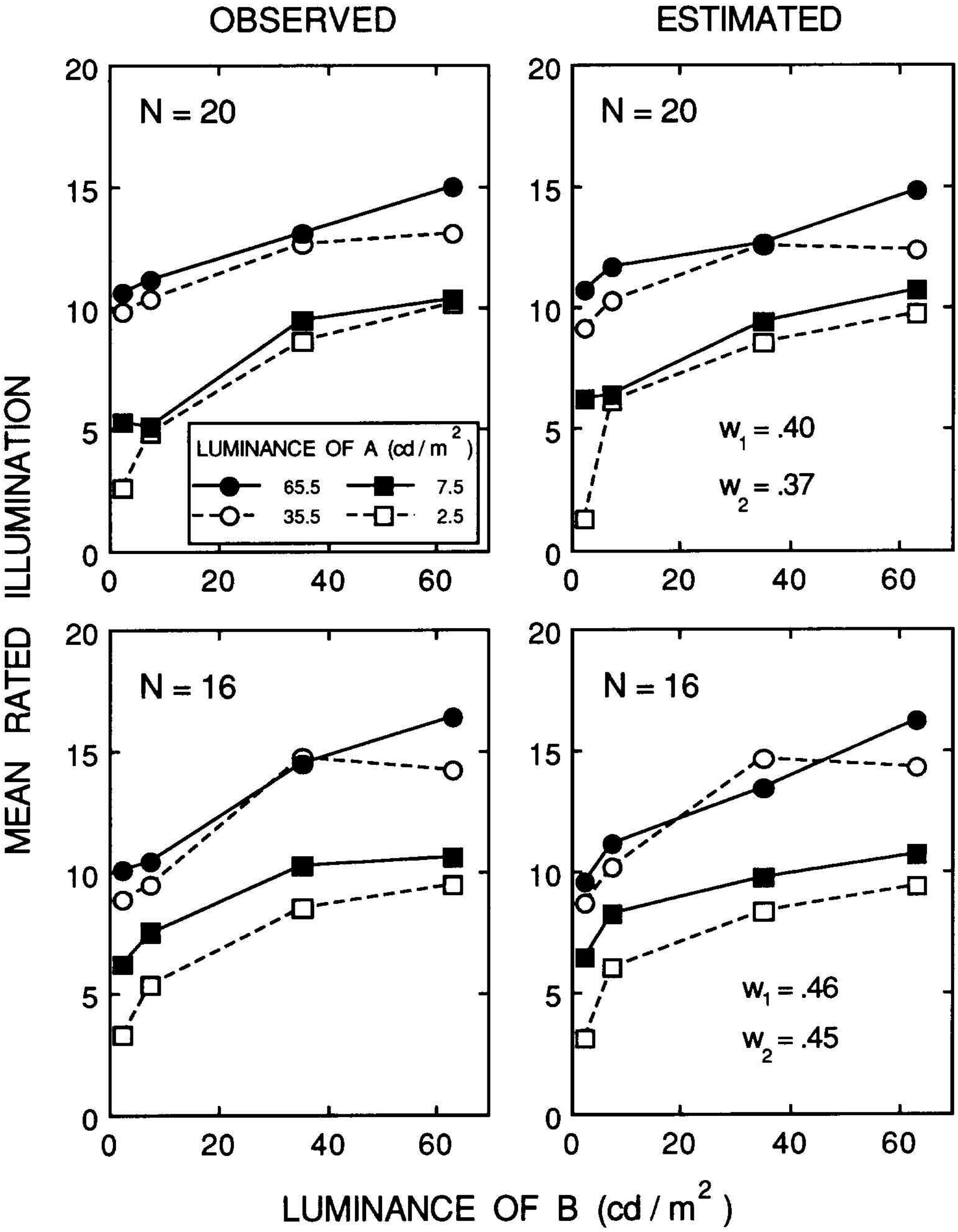
OBSERVED
ESTIMATED
N = 20
N = 20
N = 16
N = 16
LUMINANCE OF A (cd / m2)
65.5
35.5
7.5
2.5
w1 = .40
w2 = .37
w1 = .46
w2 = .45
MEAN RATED ILLUMINATION
LUMINANCE OF B (cd / m2)

Figure 3.

Table 1. Mean ratings of a and b.

		a				b				
		L_B				L_B				
		63.5	35.5	7.5	2.5	63.5	36.5	7.5	2.5	
	63.5	18.0	16.9	17.0	17.3	17.7	12.5	7.4	2.1	
	35.5	13.1	16.2	15.4	15.6	16.6	15.4	8.3	2.3	
L_A	7.5	7.6	8.2	10.9	12.1	16.4	14.8	10.5	4.5	Group 1
	2.5	2.7	3.0	4.8	6.5	16.8	15.4	12.3	6.4	
	63.5	18.3	17.3	17.7	18.7	17.1	11.8	5.9	1.0	
	35.5	14.5	16.7	15.6	17.4	17.1	16.8	7.1	1.5	
L_A	7.5	6.3	7.2	10.5	12.0	16.7	14.8	9.7	3.8	Group 2
	2.5	1.9	2.4	4.3	5.5	18.2	16.5	10.9	4.3	

Note. L_A and L_B are the luminances (cd/m^2) of A and B, respectively.

Table 2. Mean ratings of perceived illumination.

		Group 1				Group 2			
		L_B				L_B			
		63.5	35.5	7.5	2.5	63.5	36.5	7.5	2.5
	63.5	15.0	13.1	11.1	10.6	16.3	14.4	10.4	10.1
	35.5	13.0	12.6	10.3	9.8	14.2	14.7	9.4	8.9
L_A	7.5	10.4	9.5	5.1	5.3	10.6	10.3	7.6	6.3
	2.5	10.2	8.6	4.9	2.6	9.4	8.5	5.4	3.3

Note. L_A and L_B are defined as in Table 1.

Table 3. Estimates of i_S and s.

		i_S				s				
		L_B				L_B				
		63.5	35.5	7.5	2.5	63.5	36.5	7.5	2.5	
	63.5	3.1	2.85	2.6	2.35	2.5	2.25	2	1.75	
	35.5	2.85	2.6	2.35	2.1	2.25	2	1.75	1.5	
L_A	7.5	2.6	2.35	2.1	1.85	2	1.75	1.5	1.25	Group 1
	2.5	2.35	2.1	1.85	1.6	1.75	1.5	1.25	1	
	63.5	3.41	3.22	3.04	2.86	2.7	2.89	3.07	3.26	
	35.5	3.22	3.04	2.86	2.67	2.89	3.07	3.26	3.44	
L_A	7.5	3.04	2.86	2.67	2.49	3.07	3.26	3.44	3.62	Group 2
	2.5	2.86	2.67	2.49	2.3	3.26	3.44	3.62	3.8	

Note. L_A and L_B are defined as in Table 1.

the data in Table 2 when the estimated weights are practically equal.

If correct, Model 2 indicates that in the present stimulus conditions the contour between *A* and *B* was less important in determining perceived illumination – its weight being .22 for Group 1 and .08 for Group 2.

Model 2 explains the perceived illumination in scenes viewed through a hole but not that of a screen (i_S). Thus, further research is needed to extend this model to other settings.

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