

## Visual computation of surface lightness: Local contrast vs. frames of reference

Alan L. Gilchrist<sup>1</sup> & Ana Radonjic<sup>2</sup>

<sup>1</sup>*Rutgers University, Newark, USA*

<sup>2</sup>*University of Pennsylvania, Philadelphia, USA*

Seeing black, white and gray surfaces, called lightness perception, might seem simple because white surfaces reflect 90% of the light they receive while black surfaces reflect only 3%, and the human retina is composed of light sensitive cells. The problem is that, because illumination varies from time to time and from place to place, any amount of light can be reflected from any shade of gray. Thus the amount of light reflected by an object, called luminance, says nothing about its lightness. Experts agree that the lightness of a surface can be computed only by using the surrounding context, but they disagree about how the context is used. We have tested an image in which two major classes of theory, contrast theories and frame-of-reference theories, make very different predictions regarding what gray shades will be seen by human observers. We show that when frame-of-reference is varied while contrast is held constant, lightness varies strongly. But when contrast is varied but frame-of-reference is held constant, little or no variation is seen. These results suggest that efforts to discover the exact algorithm by which the human visual system segments the image received by the retina into frames of reference should be given high priority.

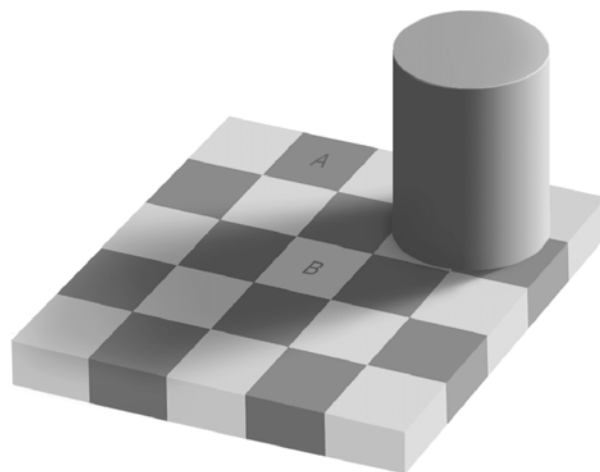
The challenge confronting the human visual system in assigning black, white, and gray shades to visible surfaces is illustrated in Figure 1. Three identical disks have been pasted into this photograph. One appears black, one appears gray and one appears white even though all three send exactly the same amount of light to the eye. Clearly the

luminance value of the light reflected by an object says nothing about its perceived lightness value.



Or consider Adelson's Checker shadow illusion in Figure 2. Although the two squares A and B are identical in luminance, they appear very different in lightness.

These examples make it obvious that the human visual system uses the surrounding context to compute the lightness of a given surface. Here we report a test between two general ways of looking at context: local contrast theories and frame-of-reference theories.

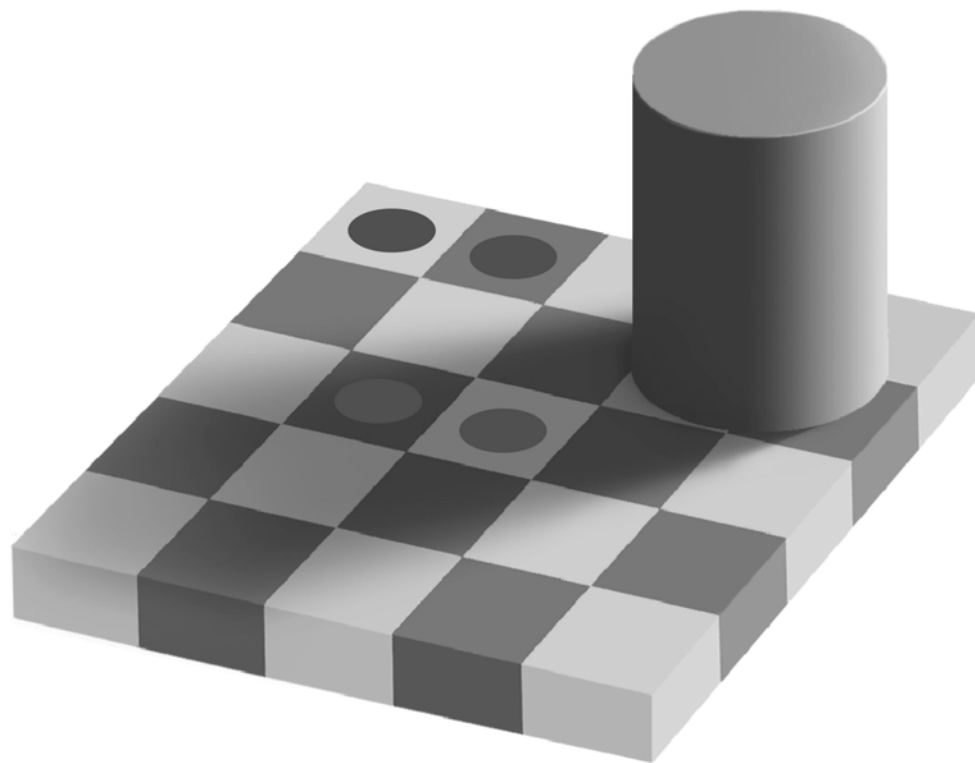


Local contrast theories. In perhaps the clearest formulation of this point of view, Wallach proposed in 1948 that object lightness is determined, not by the luminance of a surface, but by the luminance ratio between the surface and its immediate surround<sup>1</sup>. Contrast theories<sup>2,3</sup> and brightness induction theories<sup>4</sup>, which derive from Hering<sup>5</sup>, are couched in physiological terms, invoking the mechanism of lateral inhibition, but they share with Wallach the view that lightness is directly tied to local relative retinal stimulation.

Frame-of-reference theories. This approach takes into account a larger context and exploits more of the structure of the retinal image. The gestalt theorist Koffka proposed that lightness depends on higher order luminance relationships and that the field of illumination in which a surface is embedded serves as a frame of reference against which the luminance of the surface is evaluated<sup>6</sup>. Gilchrist has demonstrated that, within such a framework, the highest luminance serves as an anchor and is assigned the value of white. The lightness of other surfaces within the framework depends on the luminance ratio between the surface and the highest luminance<sup>7,8</sup>.

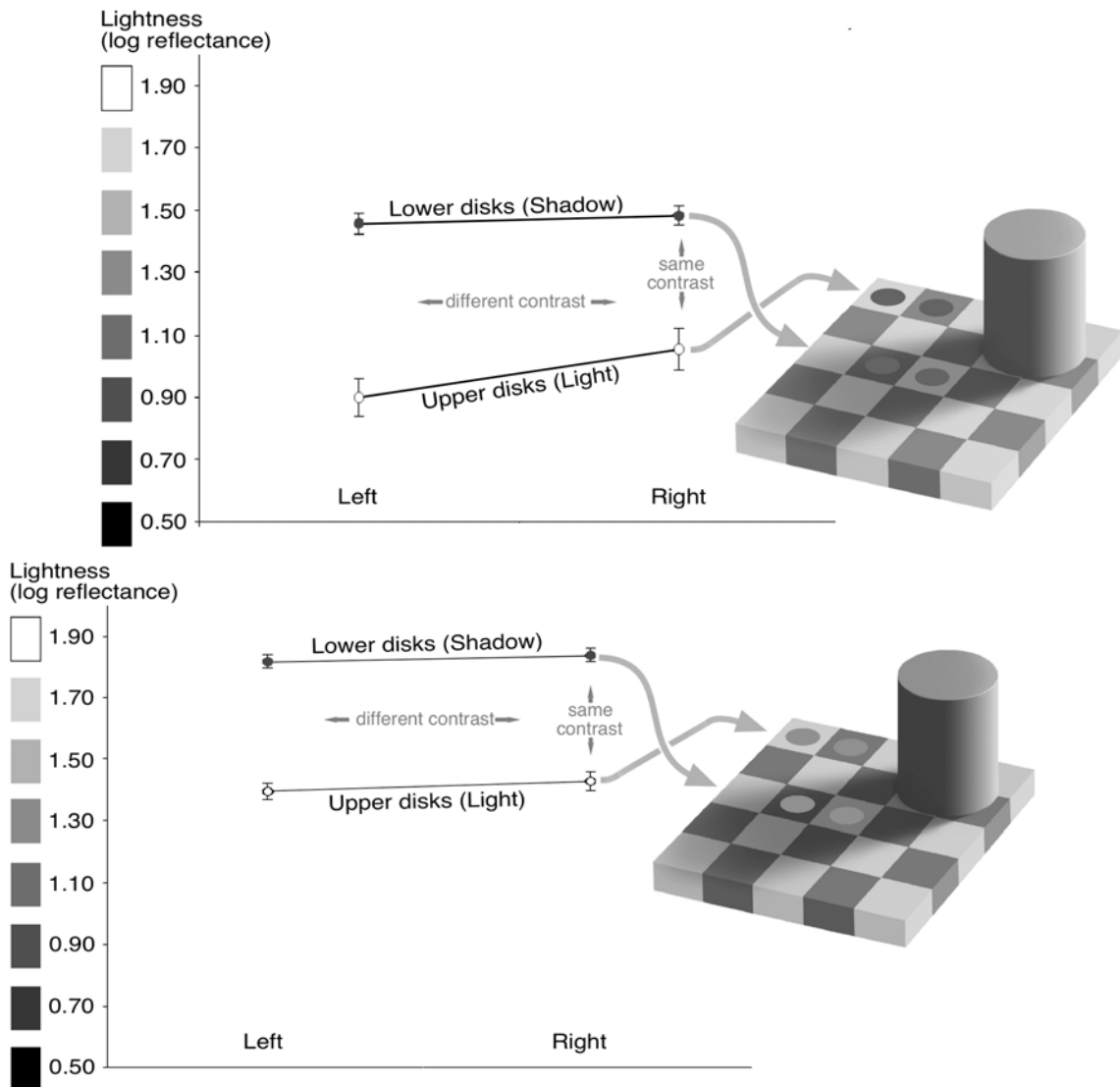
These two classes of theory are both consistent with the appearance of the disks in Figure 1. Notice that the three disks have very different disk/surround luminance ratios, but they also lie in very different frameworks of illumination. We sought an image in which the two approaches would predict different lightness values. To this end we pasted four identical disks into the Checker shadow image, as shown in Figure 3, and asked human observers to match each disk to a Munsell chart of gray shades ranging from white to black. If lightness depends primarily on local contrast, the upper and lower rightmost disks should appear as the same shade of gray, because they have the same local contrast (remember that the squares on which they lie are equal in luminance and all the disks are equal in luminance). And the two upper disks that have different local contrast should appear very different from each other, as should the two lower

disks. But if lightness is determined primarily by frame of reference, then the two upper disks in the light should appear approximately equal, and much darker than the two lower disks in the shadow, which should also appear approximately equal to each other. The results shown in the graph, confirming what is obvious from mere inspection, are consistent with the frame of reference hypothesis.



In short, any effect of local contrast is small relative to the effect of illumination framework.

Although the data were analyzed in terms of log reflectance, the results are more intuitively described in Munsell values, ranging from a typical black at Munsell 2.0 to a typical white at Munsell 9.5. The mean lightness matches for each disk are shown in Figure 4a.



The average lightness of the disks in the shadow was 2.3 Munsell units (0.49 units of log reflectance) higher than that of the disks in the light. We compared the lightness of each disk with every other disk on the checkerboard using pairwise comparisons, with Boniferroni adjustment for multiple comparisons. We found that each disk in the shadow was perceived as lighter than each disk in the light ( $p < 0.001$ ), but that the two disks in the shadow did not significantly differ in matched lightness, despite their different local contrasts. Outside the shadow, the disk on the light square

appeared darker than the disk on the dark square ( $p = 0.015$ ) but the difference was very small, 0.6 Munsell units (0.15 units of log reflectance).

To confirm that these results are not the product of a particular value of disk luminance, we repeated the experiment using a lighter set of disks, as shown in Figure 4b. We obtained the same pattern of results. The average lightness of the disks in the shadow was 2.8 Munsell units (0.42 units of log reflectance) higher than that of the disks in the light. Pairwise comparisons showed that each disk in the shadow was perceived as lighter than each disk in the light ( $p < 0.001$ ). And in this case, the two disks in the shadow showed no significant difference in matched lightness, despite their different local contrasts. Nor did the two disks in the light.

These results suggest that the dramatically different appearance of the three disks in Figure 1 is due, not to their different local contrasts, but to the different frames of reference within which they lie. This in turn reveals the compelling need for a better grasp of the nature of the software by which the visual system segments a complex scene into frameworks of illumination.

Local contrast theories have the distinct advantage of being clearly operationalized, but this does not excuse their clear failure against more sophisticated models. Frame-of-reference theories are criticized as ambiguous but advances have been made. The rules of lightness computation within a framework of illumination are by now quite well worked out<sup>9, 10</sup>. Perhaps the biggest remaining challenge concerns how such frameworks are extracted from the complex image on the retina. To a first approximation, there are two main features of the image that functionally segment the image: penumbrae (blurred edges) and depth boundaries (corners and occlusion boundaries)<sup>8, 9</sup>.

More recently the basic contrast theory of Hering has morphed into more than a dozen models called spatial filtering models. The ODOG model of Blakeslee and McCourt is a prominent example<sup>11</sup>. Because these models invoke center/surround receptive fields of different spatial scales, they are not tied to local contrast. Typically one cannot predict how a given model will compute lightness values for a given image without actually feeding the image into a computer program that instantiates the model. But in general, spatial filtering models fail to predict lightness values in images containing pronounced spatial variations in illumination level, as do most real world scenes.

## **Methods**

The Adelson Checker shadow image was downloaded (source: [http://web.mit.edu/persci/people/adelson/checkersshadow\\_downloads.html](http://web.mit.edu/persci/people/adelson/checkersshadow_downloads.html)) and displayed on a 20" Apple Multiple Scan CRT monitor (resolution of 1280 x 960 pixels at 75Hz refresh rate) in a dark room, using Microsoft PowerPoint® 2004 software (Microsoft Corporation WA, USA). Four circular gray disks were compressed to ellipsoidal shape, to match the perspective projection of the checkerboard (but only roughly, being done manually in PowerPoint, using the cylinder top as a template). A dark gray set, with triple values of 80 in RGB notation, was shown to one group of 15 observers while a light gray set with values of 127 was shown to another group of 15.

At the viewing distance of 80 cm, each disk subtended 2.1° of visual angle horizontally and 1.1° of visual angle vertically, while the entire image subtended 26° horizontally and 20° vertically. Measurements with a Konica Minolta LS-100 spotmeter showed an average luminance of the disks in the dark disk condition of 13.65 cd/m<sup>2</sup> (+/- 2%, equivalent to the measuring error) and in the light disk condition 31.3 (+/- 2%). Thus, within a condition, all disks were practically equiluminant. The luminance of the light and the dark check, respectively, was 50.8 cd/m<sup>2</sup> and 22.3 cd/m<sup>2</sup> in the light and

22.3 cd/ m<sup>2</sup> and 9.5 cd/m<sup>2</sup> in the shadow. The highest luminance on the screen was 71.0 cd/m<sup>2</sup>.

A gray scale housed in a metal chamber and separately illuminated by a 15W fluorescent tube was located just to the right of the observer, who was seated and instructed “to pick a chip from the scale for each disk that is the same color (shade of gray) as that disk, like they were cut from the same piece of paper”. The scale consisted of 16 Munsell chips (each 1x3 cm) mounted on a white background and arranged in ascending reflectance order from black (Munsell 2.0) to white (Munsell 9.5). The luminance of the white chip was 395 cd/m<sup>2</sup>.

Three observers (one from the dark disks and two from the light disks condition) were excluded because their matches fell 3 standard deviations or more from the mean of the group. Each was replaced by a new observer.

#### References:

1. Wallach, H. (1948). Brightness constancy and the nature of achromatic colors. *Journal of Experimental Psychology*, 38, 310-324.
2. Jameson, D., and Hurvich, L.M. (1961). Complexities of perceived brightness. *Science*, 133, 174-179.
3. Cornsweet, T. N. (1970). *Visual Perception*. New York: Academic Press.
4. Heinemann, E. G. (1955). Simultaneous brightness induction as a function of inducing- and test- inducing luminances. *Journal of Experimental Psychology*, 50, 89-96.
5. Hering, E. (1974/1964). *Outlines of a Theory of the Light Sense*. Cambridge, MA: Harvard University Press.



6. Koffka, K. (1935). *Principles of Gestalt Psychology*. New York: Harcourt, Brace & World, Inc.
7. Li, X., and Gilchrist, A.L. (1999). Relative area and relative luminance combine to anchor surface lightness values. *Perception & Psychophysics*, *61*(5), 771-785.
8. Gilchrist, A. L., Kossyfidis C., Bonato F., Agostini T., Cataliotti, J., Li X., Spehar, B., Annan V. & Economou, E. (1999). An Anchoring Theory of Lightness Perception. *Psychological Review*, *106*(4), 795-834.
9. Gilchrist, A. L. (2006). *Seeing black and white*. New York: Oxford University Press, Inc.
10. Bressan, P. (2006). The place of white in a world of grays: a double-anchoring theory of lightness perception. *Psychological Review*, *113*, 526-553.
11. Blakeslee, B. & McCourt, M.E. (2004). A unified theory of brightness contrast and assimilation incorporating oriented multiscale spatial filtering and contrast normalization. *Vision Research*, *44*, 2483-2503.

**Author Contributions:** A.G. and A.R. designed the experiments and created the stimulus display. A.R. tested the subjects and analyzed the data. A.G. and A.R. wrote the paper.

**Competing financial interest statement:** There are no competing financial interests.

Correspondence and requests for materials should be addressed to alan@psychology.rutgers.edu.

### *Figure legends*

Figure 1: *The three disks that have been pasted into this photograph appear black, gray and white, although they are identical.*

Figure 2: *Adelson's Checker shadow illusion: Squares A and B are identical in luminance, but they appear different in lightness.*

Figure 3: *Adelson's checker shadow illusion with equiluminant probe disks (dark-disk condition). The upper and lower rightmost disks have the same local contrast, but they appear different in lightness. The two lower disks have different local contrast but they appear almost the same shade of gray; the same is true for the two upper disks.*

Figure 4. *Perceived disk lightness in the dark-disk (top: Figure 4a) and the light-disk condition (bottom: Figure 4b). Each data point represents the mean matched lightness of a separate group of 15 observers (total N=60) expressed in log reflectance with error bars indicating  $\pm 1$  between-subject SEM. For clarity, we added a gray-scale on the Y-axis that (approximately) corresponds to each value of log-reflectance. The relative position of the target disk is plotted on the X-axis. Black lines connect the data points corresponding to disks that lie in the same framework (Shadow vs. Light). Horizontal gray arrows indicate pairs of disks that have different contrast, but belong to the same framework. Vertical gray arrow indicate a pair of disks that have the same local contrast, but belong to different frameworks of illumination.*