Perception, 1983, volume 12, pages 411-416

Light source position in the perception of object shape

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Received 22 October 1982, in revised form 3 March 1983

Abstract. The apparent relief of monocularly viewed surfaces reversed when the order of light and shade was reversed relative to the position of a lamp observed the moment earlier. The pattern of shading was reversed either by illuminating from a direction opposite to that of the apparent direction of illumination or by inverting the illuminating image relative to the light source. The combination of both of these manipulations restores the original juxtaposition of light source and shading and reestablished accurate perception of relief. These results demonstrate that the perception of the relief of physical surfaces depends upon the remembered position of an apparent light source.

1 Introduction

Gibson (1950) and other authors of classic textbooks in visual perception (Boring 1942; Woodworth and Schlosberg 1954) have suggested that the perception of relief depends upon allowing for the position of the light source relative to the surface of interest. Surfaces reflect light to the observer as a function of their orientations towards or away from the light source. The correct perception of relief may thus depend upon the spatial order of light and shade relative to the direction of illumination (position of the light source). The evidence usually cited for this shape-from-shading formula is in the form of a demonstration of the reversal of relief that can be achieved by turning pictures upside down (Gibson 1950). This evidence is somewhat indirect because it requires the assumption of overhead illumination. In some pictures, the source of illumination is not shown directly. Areas that reflect more light relative to the rest of a scene are seen as oriented so that a line normal to the surface points generally upward. Areas that reflect less light than other areas in a scene are seen as oriented so that a line normal to the surface points generally downward. This means that a bright area just above a dim area will produce the impression of a protuberance, and a dim area just above a bright area will produce the impression of an indentation. When a photograph is turned upside down the order of light and shadow is reversed. Perceptually, the relief is also reversed: protuberances become indentations and indentations become protuberances. This phenomenon may result from perceptual premises that brighter areas face toward a light source, and dimmer areas face away (the shape-from-shading formula), and that the direction of illumination is from above. This latter proposition, that we assume overhead lighting, seems to have been first stated by Brewster (1826). There have been numerous attempts to determine whether this perceptual assumption is learned or innate (Metzger 1936; von Fieandt 1949; Hess 1950; Hershberger 1970; Benson and Yonas 1973; Hagen 1976). Many of these studies find developmental changes in the use of the assumption. Most of these experiments treat the assumption of overhead lighting (assumption 2) as a special case of the use of the relief-from-shading formula (assumption 1) in which the direction of illumination is not specified in the photograph, and overhead lighting is assumed by default.

One experiment, by Yonas et al (1979), has shown that children interpret shape in pictures as if illumination of the pictured surfaces were from above the observer's head (an egocentric definition of overhead lighting or from the ceiling (an environmental definition of overhead lighting). This experiment also tested the shape-from-shading formula directly, and independently of the overhead-lighting assumption. Although the subjects viewed photographs rather than physical forms, a light source was placed in a position in which it might appear to illuminate the surface depicted in the photograph. The shading varied in the horizontal axis and the apparent light source was to the side so that overhead-lighting references were orthogonal to the orientation of shading. The observers used the physical location of an apparent light source to interpret the shading in a picture. There were clear developmental increases in the use of the position of the apparent light source.

Informal observations of the perception of relief by adults in a viewing condition similar to the Yonas et al apparent-light-source condition had been reported much earlier by Rittenhouse (1786), Brewster (1832), and Oppel (1856). These authors reported similar informal observations of the perception of relief under much the same viewing conditions. Shallow elevations and depressions in a surface were illuminated from a single light source. When the surface, but not the light source, was viewed through lenses which inverted the image of the surface upon the retina top-to-bottom and left-to-right, the relief was perceptually reversed. When the direct illumination from the apparent light source was interrupted and the object illuminated from the opposite direction by indirect light reflected by a mirror, the relief viewed directly without the lenses was again reversed. When this latter arrangement was viewed through inverting lenses, no illusion was observed. These authors do not give detailed information about spatial characteristics of the viewing conditions, and in each case the author served as the observer and was therefore aware beforehand of the actual relief (making the experiment less than rigorous by contemporary standards).

In a brief experiment we have replicated the finding of Yonas et al (1979) with adult observers rather than children, with real objects rather than photographs, and using experimental manipulations which are similar to the informal observations of early researchers in the perception of relief (Rittenhouse 1786; Brewster 1826, 1832, 1844; Oppel, 1856). A major difference between this experiment and previous investigations is that the apparent light source is viewed immediately before but not during observation of the shading.

The surfaces of a physical object were illuminated by a light source. Observers viewed the light source before each experimental trial of the experiment, and then viewed the objects. This manipulation requires that the light source position be remembered, at least briefly. This seems an important aspect of any shape interpretation process; perceptual procedure that would require the light source to be directly and continuously visible during perception would be limited indeed. The pattern of shading upon surfaces (the order of light and shade) was reversed relative to the apparent direction of illumination either by illuminating from a direction opposite to that of the apparent direction of illumination, or by inverting the retinal image of the object relative to the light source. The combination of both of these manipulations restores the original juxtaposition of light source and shading and reestablished accurate perception of relief. The object of the experiment was to test whether the spatial interpretation of image shading as surface shape depends upon the apparent position of the source of illumination. This prediction was assessed by using the observers' reports of the relief of surfaces.

2 Method

2.1 *Stimuli*

A common muffin pan having twelve receptacles and painted white on both sides was used to test perception of relief (the dimensions are shown in figure 1).

Twelve indentations are presented if one side of the pan is turned toward the observer, and twelve similarly sized and shaped protuberances are presented if the other side is turned toward the observer. The outside shape of indentations and the inside shape of protuberances is a frustum of a cone. Figure 1 also shows the other dimensions of the viewing arrangements. The pan was viewed monocularly from a distance of 182 cm through a 2.5 cm aperture.

2.2 *Subjects*
Twenty experimentally naive students enrolled in an introductory psychology class at the University of Iowa participated in the experiment to fulfill a course requirement. All subjects reported normal or corrected-to-normal vision without glasses.

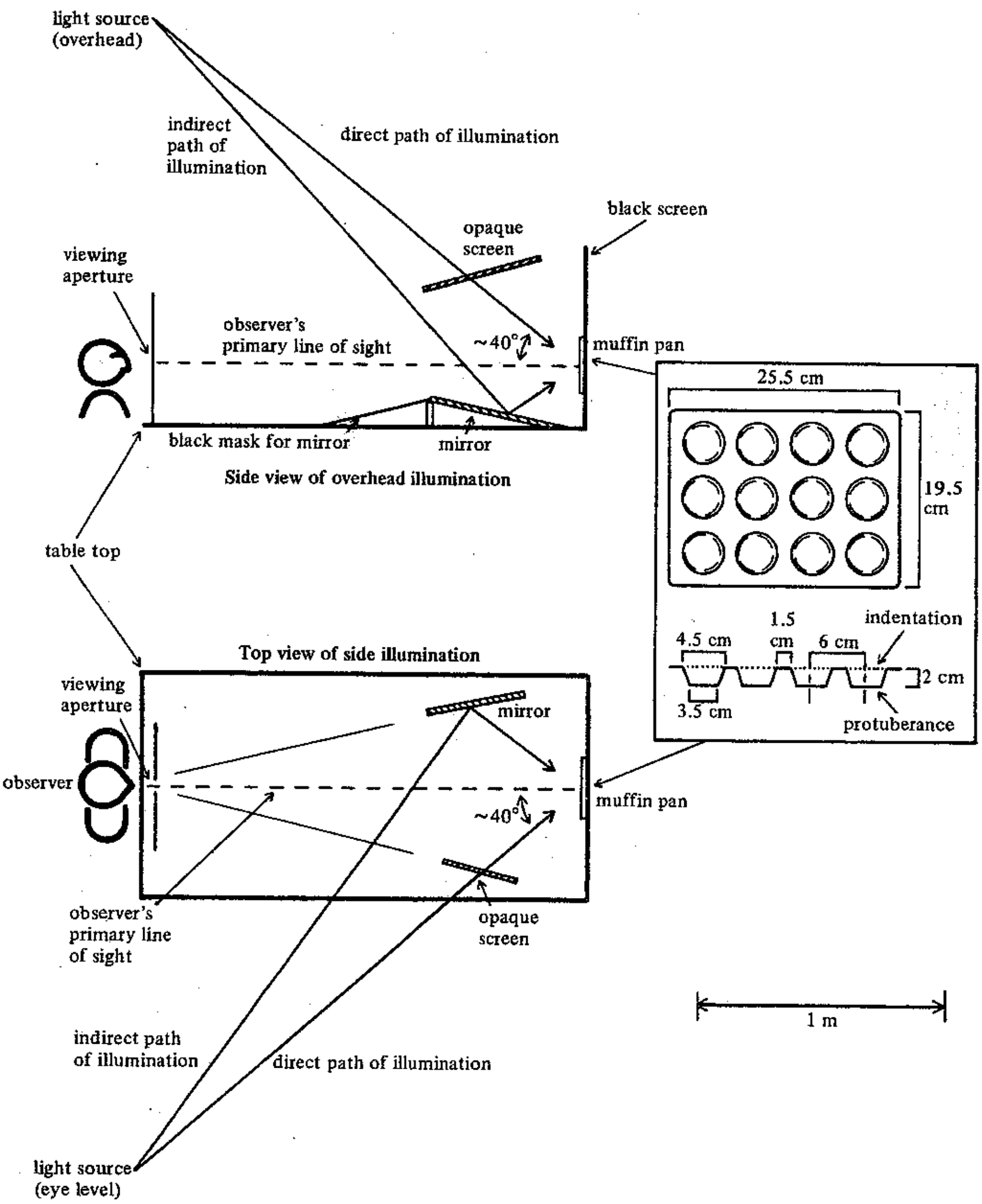

Figure 1. Experimental setup.

2.3 *Procedure and experimental design*

Subjects were familiarized with both sides of the object and asked to report on subsequent trials whether they were presented with the indentations or protuberances. In each trial the subject observed the object until making a response. There were sixteen trials resulting from the factorial combination of four binary factors. On half of the trials one side of the pan was presented; on the other half the other side was presented. On half of the trials the object was viewed directly, and on the other half the object was viewed through a pair of convex lenses (of 11 and 23 diopters) which served to invert the image of the object. (These lenses could be mounted on the opposite side of the aperture from the observer.) On half of the trials the object was illuminated by light located directly above the subject's head (upper panel, figure 1), and on the other half the object was illuminated by a light directly to the side of the observer (lower panel, figure 1). In both cases the light source was directly visible to subjects before and between test trials. Because of the nature of the aperture, chin rest, and optics, the object and light source were not simultaneously visible. (Subjects were also explicitly shown the positions of the two light sources before the experiment.) Finally, on half of the trials the pans were illuminated directly by one or the other light source, and on the other half of the trials a mirror reflected light onto the pan from the direction opposite the light source and a screen was placed between the light source and the pan so as to interrupt the direct illumination. In the latter cases, the planes of the mirror and screen were placed in the lines of sight from the viewing aperture, so that they were visible only from the side and their functions were not apparent to subjects. Before and between test trials the mirrors were covered by black material. (Questioned afterwards, subjects reported that they had not been aware that a mirror was being used.)

3 Results

Table 1 shows the frequency of errors in detection of indentation and protuberance. A conversion of relief in this table is denoted by very high frequencies of incorrect report. Note that when the path of illumination was unaltered and the observer's line of sight was unaltered (direct lighting, direct viewing), all twenty subjects correctly identified the relief in both overhead and side lighting (shown in each upper left quadrant of each quadrant of table 1). In all cases of overhead and side lighting of indentations and protuberances, interruption of direct lighting and reflection of light from an opposite angle (indirect lighting, direct viewing) produced conversion of relief. This is 19 of 20, 13 of 20, 18 of 20, and 18 of 20 possible conversions of relief. In all cases inverting the image about the principal line of sight (direct lighting, inverted viewing) also produced conversion of relief. This is 15 of 20, 11 of 20, 18 of 20, and 15 of 20 possible conversions of relief. The conversion of relief was confirmed

Table 1. Frequencies of error in report of relief by twenty subjects.

	Path of illumination	Overhead lighting		Side lighting	
		direct viewing	inverting lens	direct viewing	inverting lens
Indentations	direct	0	15	0	11
	indirect[a]	19	2	13	2
Protuberances	direct	0	18	0	15
	indirect[a]	18	2	18	4

[a] Indirect light produced by mirror and screens.

in these eight comparisons between direct lighting and viewing, and indirect lighting or inverting-lens viewing, by means of McNemar's (1962) z-test for difference between nonindependent frequencies. All eight tests were significant ($p < 0.0001$). In all cases veridical perception of relief was reestablished with the application of both indirect lighting and inverting-lens viewing (as evidenced by the low error frequencies in the lower right quadrants of each quadrant of table 1). Four tests of difference between nonindependent frequencies show no significant differences ($p > 0.50$) between direct lighting–direct viewing and indirect lighting–inverting-lens viewing. When both relief-reversing manipulations are combined, the order of light and shade relative to the light source undergoes two reversals which results in the original relationship of shading and light source. The restoration of accurate perception in this case clearly demonstrates that it is the relationship of shading and light source that is important, not the particular method of altering the images. It may be noted that the conversion of relief is slightly less frequent with side lighting than with overhead lighting, but this difference is not statistically significant ($p > 0.05$).

4 Discussion

It is clear from these data that the accurate perception of relief of an ambiguous surface depends upon the spatial disposition of shading and apparent light source. Subjects seem to take into account the apparent position of the light source in interpreting variation in shading as relief. One aspect of the data that is of particular interest: the protuberances suffer the same conversion of relief as the indentations. This is true even though the protuberances cast shadows across the surface beyond the bases of the protuberances. Cast shadows may indicate the direction of illumination by the convergence of the shadow (Arnheim 1954). This convergence would prevent conversion of relief if subjects were to rely on these cast shadows rather than the visible apparent light source in determining direction of illumination. It may be that the relief of our test pattern was so shallow and the angle of illumination not so oblique as to cast shadows far enough to indicate the position of the light source. To test this latter notion we exposed five experimental subjects to the experimental conditions already described, except that rods were placed in the path of illumination so as to cast extensive shadows across the pans. The positions of the shadows cast across the surface of the pans by the rods could indicate the actual direction of illumination. However, the viewing conditions which had produced conversion of relief in our main experiment continued to produce conversion of relief even with extended cast shadows across the surface. Cast shadows are not necessarily effective cues to direction of illumination when subjects have directly viewed an apparent light source; subjects rely on the remembered position of light source in interpreting the variation of shading as relief.

In this experiment subjects perceived surface shape from shading relative to the apparent light source; they did not automatically assume overhead lighting. For the perceptual interpretations of this experiment some minimal memory is required: a memory whose contents contains the direction of illumination which controls interpretation of data registered at the senses. Such a direct observation of light source position seems to be a singularly potent determinant of shape perception; even contrary evidence from cast shadows that the light falling on the pans was from another direction did not supersede the position apparent from direct observation.

In an attempt to replicate and extend the findings reported here, we recently asked observers to indicate protuberance or indentation by button pressing, when photographs of the muffin pans were rear-projected upon a viewing screen. When eight naive observers were individually presented with vertically oriented shading in the pans, they indicated shape percepts consistent with overhead lighting. Another group of eight naive observers were presented with horizontally oriented shading in the photographs of the muffin tins and asked to assume that the light source for the photographs was from one side. In this case observers indicated shape percepts consistent with the assumed position of the light source. There can be little doubt that the light source position is constructed in memory, since it is never physically present, or that the effect can be long lasting since the instruction concerning the light source position contined to determine shape perception through 120 slide presentations, a 15 minute session.

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