Orientation tuning of shape from shading

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Four experiments were performed to assess the effect of different orientations and direction of lighting on the visual processing of shaded or bipartite disks. In the first two experiments, observers were presented with nine different shading orientations from 0° to 180°. Targets were detected in a rapid and parallel fashion for shaded disks when the orientation of the shading gradient was not horizontal (90°) or oriented at 67.5°. Search asymmetries favoring the detection of "pock" targets over "ball" targets were found for all orientations. The search rates for bipartite disks were similar to the shaded disks at 0°, 22.5°, and 90° but not for intermediate orientations, and no search asymmetries were found. These differences suggest that shaded displays and bipartite displays are processed by different underlying mechanisms. The third experiment showed that the direction of the light source (left or right) had no influence on search asymmetries around the 90° point. Shading gradient orientation affected magnitude estimates of depth in the fourth experiment. These experiments show that the visual system's "assumption" of overhead lighting is broadly tuned.

The visual system's ability to derive 3-D shape from shading depends on information present in the visual display. In particular, when the visual system is confronted with displays similar to those in Figure 1, an "assumption" is made that there is a unitary light source located above the display (Brewster, 1847; Ramachandran, 1988). The assumption of overhead lighting is consistent with the usual natural light in our environment. Most observers describe Figure 1 as a "ball" in a field of "pocks," which is consistent with the overhead-lighting assumption. Although this presents a compelling description of how depth is derived in displays such as that in Figure 1, the visual world does not always have a light source located directly overhead. In the present research, we assess the effect of changing the orientation of the shading gradients, and, by implication, the direction of the light source, on the ability to process shaded and bipartite displays.

Relatively few studies have directly examined the effect of changing the orientation of the light source in the processing of a display containing shaded objects. Ber-

baum, Bever, and Chung (1983) demonstrated that the direction of depth of a viewed muffin tin depended on the subject's understanding of the position of the light source and the direction of the shading gradient. Even though the position of the light source remained the same, after the subjects had donned inverting prisms, they reported a reversal of depth.

Apart from displays that use vertical or horizontal light source orientations, relatively little evidence exists concerning intervening orientations. Howard, Bergström, and Ohmi (1990) found that the perception of the direction of depth was consistent with an overhead-lighting assumption for a wide variety of orientations of shading axes. The assumption continued to hold until the shading axis was rotated 60° with respect to the median plane of the subject's head. Wenderoth and Hickey (1993), who employed a task in which subjects' reaction times and accuracies in determining symmetry of shaded displays were measured, found a gradual reduction in performance as the orientation of shading moved from orthogonal to the median plane of the head to parallel.

The assumption of overhead lighting may allow the visual system to derive shape information from shading in a rapid manner. Aks and Enns (1992) and Kleffner and Ramachandran (1992) have shown that finding a shaded disk target within a display of oppositely shaded distractors occurs rapidly and in parallel. Furthermore, using a method of concurrent tasks, Braun (1993) found that subjects could determine the position of an oppositely shaded disk while simultaneously performing an attentionally demanding task. Preattentive search does not occur, however, if the direction of the "light source" for the display is from the side (Kleffner & Ramachandran, 1992). Further-

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Figure 1. A display of shaded disks. The target item appears to most observers as a ball and the distractors as pocks. Inverting the display inverts the interpretation. This is consistent with an overhead-lighting assumption. The spatial relationship of the items in this picture approximates that used in Experiment 4. The quality of the displays is improved when presented on a video display.

more, “top-lit” displays show rapid segregation, whereas “side-lit” displays are difficult to segregate (Ramachandran, 1988).

Kleffner and Ramachandran (1992) have suggested that the preattentive nature of shading analysis indicates that the shaded solids are “perceptual primitives” (see, e.g., Beck, Prazdny, & Rosenfeld, 1983; Julesz, 1984; Treisman, 1986). Aks and Enns (1992) give an alternative suggestion—that the shading information is used as part of a “quick and dirty” analysis of the visual scene for predictors of depth and that the depth, per se, is not derived preattentively.

In the present study, we examined the nature of processing of shaded displays as a function of the orientation of the light source. A visual search task similar to that used by Aks and Enns (1992) and Kleffner and Ramachandran (1992) was used in the first three experiments. In the third experiment, we assessed the potential role that different directions of the light source (left vs. right) might play. And, in the fourth experiment, a magnitude estimation procedure was used to estimate the depth of disks shaded at different orientations. Shaded or bipartite disks with luminance orientations ranging from 0° (target “top-lit”) through to 180° (distractors “top-lit”) in 22.5° steps were used (see Figure 2). Determining the orientation tuning function for the processing of shading should provide important information concerning the heuristics that the visual system uses to derive shape from shading. Furthermore, any differences demonstrated between display types (shaded vs. bipartite), as a function of orientation, should provide evidence concerning differ-

ent mechanisms that might underlie the processing these displays.

EXPERIMENT 1 Visual Search for Shaded Disks

The visual search for “top-lit,” but not “side-lit,” objects is rapid and suggestive of parallel processing (Aks & Enns, 1992; Kleffner & Ramachandran, 1992). In Experiment 1, we assessed search rates for displays that differed in the orientation of shading. Given the prevalence of lighting source orientations in the natural world, as well as previous findings concerning the depth percepts associated with different lighting orientations (Howard et al., 1990), we expected that a wide range of lighting orientations would be processed rapidly and in parallel, which is consistent with an overhead-lighting assumption.

Method

Participants. Ninety experimentally naive participants volunteered. The participants had normal or corrected-to-normal vision and received course credit in an introductory psychology course for their involvement.

Apparatus. An Apple Macintosh IIx microcomputer, at a viewing distance of 80 cm, was used to generate the displays on an Apple 14-in. high-resolution monitor, which measured 11.4° (height) × 22.6° (width) of visual angle. Display presentation and data collection were controlled by VSearch software (Enns, Ochs, & Rensink, 1990). Nine shaded disk display conditions were created. Each condition contained different target and distractor items on a homogenous gray background (see Figure 2, left column). The displays differed in terms of the orientations of their luminance profiles. In the first condition, the displays consisted of a target with luminance profile that was

Figure 2. Examples of target and distractor items used in Experiment 1 (left column) and Experiment 2 (right column).

bright at the top and dark at the bottom, with the opposite profile for the distractors (see Figure 2, Condition 0°). The orientation of the luminance profile for each subsequent condition changed in increments of 22.5° (see Figure 2, Conditions 22.5°–157.5°). The displays in the ninth condition contained a target with a luminance profile that was bright on the bottom and dark on the top, with the opposite profile for the distractors (see Figure 2, Condition 180°).

Each target and distractor item subtended 0.6° of visual angle. The items were placed in random positions without overlap. The shaded targets and distractors were constructed from 256 linear steps of luminance ranging from 4.1 to 48.7 cd/m² and were presented on a gray background of 19.7 cd/m². The fixation dot in the displays extended 0.29° of visual angle while the feedback indicator had a diameter of 0.44° of visual angle. Both of these signals were presented in the center of the visual array.

Each trial started with a 780-msec delay, followed by a fixation point that was displayed for 900 msec and then a blank screen that lasted 150 msec. The main display then appeared for 4,500 msec or

until a response was made and was followed by a 450-msec feedback display before the next trial began.

Procedure. The participants were randomly assigned to one of the nine conditions. The experimental design within each condition was identical. On each trial 2, 6, or 12 items were displayed, with half of the trials containing one target, and the remainder, no target. The various types of trials were presented in a random order.

The participants were seated 80 cm in front of the computer screen in a dark room, and their heads were placed in a headrest with temple stops to reduce head movements and ensure vertical alignment of the head. After being instructed to respond quickly and accurately, each participant was presented with a series of trials. Two keys on the keyboard were used to indicate whether the target was present or absent. Reaction times and accuracy were recorded by the computer. If a response was not made within the allotted time, the data from that trial were discarded.

The participants were presented with six blocks of displays of 60 trials each. Prior to the collection of data, each participant practiced

Table 1
Mean Accuracy Scores (Percent Correct),
With Standard Errors, for Shaded Disks in Experiment 1

Display Size (No. Items)	Orientation																	
	0°		22.5°		45°		67.5°		90°		112.5°		135°		157.5°		180°	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Target-Present Trials																		
2	94.9	0.9	94.2	2.0	97.5	0.8	98.8	0.7	94.8	2.0	97.0	1.1	96.4	1.6	94.9	1.7	97.8	0.7
6	95.2	1.7	94.4	2.8	95.8	1.6	91.1	1.8	90.3	2.4	96.0	1.5	96.9	1.3	95.5	2.4	98.9	0.5
12	93.1	1.9	94.1	2.6	97.0	1.2	86.0	3.2	86.9	2.5	94.9	1.6	97.3	1.3	91.9	3.0	98.0	0.3
Target-Absent Trials																		
2	95.5	1.4	98.2	0.6	96.5	1.3	96.7	1.3	95.3	1.7	95.0	1.2	98.7	0.3	94.8	1.2	96.6	1.2
6	96.9	1.2	99.0	0.3	98.0	0.9	97.9	1.2	96.1	2.4	98.7	0.1	98.3	1.5	98.6	0.7	97.5	0.8
12	96.7	1.2	99.0	0.6	97.7	1.0	98.2	0.7	94.2	3.1	97.5	1.1	98.9	0.5	95.8	1.9	99.4	0.3

the visual search task by using test displays until he/she felt comfortable (usually less than 10 trials).

Results

Three dependent measures were assessed: accuracy scores, reaction times, and search rates. Search rates were calculated by determining the slope of the reaction time function for each condition. The hypotheses of interest were tested in large part with the search-rate scores. Therefore, the results for the other dependent measures are discussed only in limited form.

Accuracy scores. The mean accuracy scores are presented in Table 1. Overall accuracy was very high, although there were slightly lower scores for the 67.5° and 90° orientations in the target-present condition. These differences were supported by a three-way interaction between target presence, size of display, and orientation [$F(16,162) = 27.45, p < .01$]. Accuracy was affected by size of the display [$F(2,162) = 5.79, p < .01$] and by target presence [$F(1,81) = 26.56, p < .01$]. These two factors showed a significant interaction [$F(2,162) = 20.96, p < .01$]. Size of the display also interacted significantly with orientation [$F(16,162) = 3.66, p < .01$]. No further significant main effects or interactions were observed.

Reaction time. Mean reaction times for the shaded disks are shown in Figure 3 (target-present data are presented in panel A; target-absent data in panel B). The reaction times for the 6- and 12-item display sizes in this condition were longer for the 67.5° and 90° orientations. This effect was greater for the target-absent trials than for the target-present trials. This pattern of results was confirmed by a significant three-way interaction between target presence, size of display, and orientation [$F(16,162) = 4.79, p < .01$]. All other factors and interactions were significant ($p < .01$).

Search rates. The search rates for the nine orientations are shown in Figure 4. As can be seen in this figure, the 67.5° and 90° orientation conditions had slower search rates than any of the other conditions. This effect was particularly pronounced for the target-absent conditions. This

result was confirmed by a significant orientation $\times$ target presence interaction [$F(8,81) = 4.80, p < .01$]. Post hoc testing (Newman-Keuls, $p < .05$) revealed that the 67.5° and 90° conditions differed significantly from all other conditions, which were not statistically different from one another. The main effect of orientation was significant [$F(8,81) = 16.16, p < .01$], as was the main effect of target presence [$F(1,81) = 61.88, p < .01$]. Simple main effects analyses showed that the target-present data were not significantly different from the target-absent data except at the 22.5°, 67.5°, and 90° orientations [$F(1,81) = 12.31, 38.93, 37.36$, respectively, all $ps < .01$].

In Figure 4 there appears to be an asymmetry in search rates between the values below 90° and those above 90°. The search rates are faster when searching for a "pock" among "balls" (112.5°–180° conditions) than when searching for a "ball" among "pocks" (0°–67.5° conditions). This search asymmetry was confirmed by a separate analysis of variance (ANOVA). Two groups were formed on the basis of whether the target in the display had the features of a "ball" or the features of a "pock." The "ball" group consisted of all four conditions in which the target had an orientation less than 90° (see Figure 2, Conditions 0°–67.5°), whereas the "pock" group consisted of the four conditions in which the target had an orientation greater than 90° (see Figure 2, Conditions 112.5°–180°).

A significant difference was found for search rates as a function of group designation ("ball" vs. "pock") [$F(1,81) = 26.91, p < .01$]. This asymmetry continued to hold true, even after eliminating the 67.5° and 112.5° data points from the analysis [$F(1,81) = 4.86, p < .05$], and did not interact significantly with target presence [$F(1,81) = 3.58, p < .05$].

Discussion

The first experiment replicated and extended the findings of Aks and Enns (1992) and Kleffner and Ramachandran (1992). The visual system appears to use an assumption of an overhead light source for a wide variety of orientations, which allows for rapid and parallel search.

Figure 3. Mean reaction times for different lighting orientations as a function of display size for the shaded disk displays in Experiment 1. Panel A, target present; panel B: Target absent.

These data are also consistent with Howard et al.'s (1990) previous report on the interpretation of shaded displays at different lighting orientations.

The search asymmetry previously reported for the 0° and 180° conditions (Kleffner & Ramachandran, 1992) was extended by the present findings. It appears that there is a search advantage for all orientations of lighting in which the shaded disk target can be interpreted as a pock (i.e., in the 112.5° – 180° orientations). This asymmetry might explain the asymmetrical nature of the search rates for the 67.5° and 112.5° orientations. Although these orientations are equidistant from 90° , they generated remarkably different search rates. The search rate disad-

vantage for the 0° – 67.5° conditions was, presumably, due to reducing the boundary of the "light-from-above" assumption. Thus, a wider range of shading orientations below 90° cannot be interpreted by the visual system as being generated by a unitary overhead light source, and the system analyzes these orientations in a slow, serial fashion. The processing advantage for shading orientations greater than 90° may have allowed the system to invoke a unitary light source assumption for lighting orientations closer to 90° and, thus, allowed for a rapid, parallel processing of these displays.

Another explanation for the asymmetry in search rates for the 67.5° and 112.5° orientations comes from a recent report by Sun and Perona (1996b). These authors found an asymmetry in a stimulus onset asynchrony masking task such that shaded objects that were lit from the upper left were processed more quickly than those that were lit from the upper right. In the present experiment, the 67.5° display was a ball target lit from the upper right, whereas the 112.5° display was a pock target lit from the upper left. Thus, the difference in search rates might be attributable to the direction of the light source rather than to the depth interpretation of the display. We addressed this issue in Experiment 3.

EXPERIMENT 2

Visual Search for Bipartite Disks

Both Aks and Enns (1992) and Kleffner and Ramachandran (1992) found relatively rapid search rates for "top-lit" bipartite displays. This finding seems contradictory to previous reports that have demonstrated relatively poor region segregation for displays with bipartite disks (e.g., Ramachandran, 1988). Aks and Enns suggested that this rapid search may be indicative of a difference that underlies the processing of a visual-search display as opposed to a region-segregation display. Furthermore, both Aks and Enns and Kleffner and Ramachandran suggested that the bipartite displays may generate a signal similar to, but weaker than, the signal generated by the shaded disks. Kleffner and Ramachandran also suggested that the bipartite displays may stimulate the same neural mechanisms as do the shaded displays, albeit at a "suboptimal" level.

In Experiment 2, we examined the effect of orientation on the visual search for bipartite displays. If the bipartite displays were activating neural mechanisms similar to those activated by the shaded displays, one might expect to find an orientation tuning function similar to that demonstrated in Experiment 1. Other than the displays used, the design of this experiment was identical to that of the first.

Method

Participants. Ninety experimentally naive participants volunteered. The participants had normal or corrected-to-normal vision and received course credit in an introductory psychology course for their involvement.

Figure 4. Mean search rates as a function of lighting orientation for the shaded disk displays in Experiment 1.

Apparatus. The displays are shown in Figure 2 (right column). The apparatus was otherwise identical to that used in Experiment 1.

Procedure. The procedure was identical to that used in Experiment 1.

Results

Three dependent measures were assessed: accuracy scores, reaction times, and search rates. Again, the hypotheses of interest were tested in large part by the search-rate scores. Therefore, the results for the other dependent measures are discussed only in limited form.

Accuracy scores. The mean accuracy scores are presented in Table 2. Overall, accuracy was very high. Display size had a significant effect on accuracy scores [$F(1,81) = 3.52, p < .05$], as did target presence [$F(1,81) = 6.36, p < .05$]. These two factors interacted significantly [$F(2,162) = 14.89, p < .01$]. Orientation did not affect

accuracy significantly, nor did it interact with any other factors.

Reaction times. Mean reaction times for the bipartite disks are shown in Figure 5 (target-present data are presented in Panel A; target-absent data, in Panel B). As can be seen in this figure, the mean reaction time for the 90° orientation was slower in the target-absent condition than in the other conditions. This was confirmed by a significant orientation $\times$ target presence $\times$ display size interaction [$F(16,162) = 2.39, p < .01$]. All other factors and interactions were also significant ($p < .05$).

Search rates. The search rates for the nine orientations are shown in Figure 6. The search rates were slowest for the 90° orientations, especially in the target-absent condition. This result was confirmed by a significant orientation $\times$ target presence interaction [$F(8,81) = 2.47, p < .05$]. Post hoc testing (Newman-Keuls, $p < .05$) revealed

Table 2
Mean Accuracy Scores (Percent Correct),
With Standard Errors, for Bipartite Disks in Experiment 2

Display Size (No. Items)	Orientation															
	0°		22.5°		45°		67.5°		90°		112.5°		135°		157.5°	
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Target-Present Trials																
2	94.3	2.1	97.1	1.4	97.3	1.3	96.8	0.93	97.6	0.8	98.6	0.7	97.3	0.8	96.5	1.7
6	95.5	1.2	97.0	0.9	96.2	1.8	94.7	1.6	93.5	1.7	93.2	1.7	96.5	1.0	97.2	1.3
12	92.8	2.4	92.1	2.1	94.0	2.2	93.8	1.7	90.7	2.2	91.2	1.8	93.7	1.9	97.0	1.1
Target-Absent Trials																
2	95.4	1.9	91.7	1.7	96.1	1.4	93.4	1.5	94.8	1.5	97.6	0.8	94.4	1.2	95.6	1.4
6	96.7	1.4	98.4	0.9	99.1	0.5	98.5	0.5	97.6	0.7	99.3	0.5	97.2	1.4	96.7	1.2
12	97.7	0.9	98.1	1.0	98.5	0.7	97.2	0.66	97.8	0.9	97.3	1.1	98.3	0.7	99.0	0.6

Figure 5. Mean reaction times for different lighting orientations as a function of display size for the bipartite disk displays in Experiment 2.

that the 90° condition differed significantly from all other conditions, which were not statistically different from one another. The main effect of orientation was significant [$F(8,81) = 3.98, p < .01$], as was the main effect of target presence [$F(1,81) = 88.37, p < .01$]. Simple main effects analyses showed that the target-present data differed from the target-absent data at all orientations except 45° [$F(1,81) = 1.37, p > .05$, for 45°, $F(1,81) \geq 4.25, p < .05$, for the remaining orientations].

As can be seen in Figure 6, the search asymmetry was not as strong in the bipartite display conditions as it was for the shaded displays. A “ball” versus “pock” target analysis similar to that described for the first experiment showed no overall asymmetry effect [$F(1,81) = 1.50, p >$

.05]. However, target presence interacted with the search asymmetry effect [$F(1,81) = 4.96, p < .05$]. The target-present data showed an asymmetry favoring the $> 90^\circ$ orientations (the mean search rate for the $> 90^\circ$ orientations was 28.55 msec/item and the mean search rate for the $< 90^\circ$ orientations was 30.05 msec/item). However, the target-absent data showed a search asymmetry favoring the $< 90^\circ$ orientations (the mean search rate for the $< 90^\circ$ orientations was 50.73 msec/item; the mean search rate for the $> 90^\circ$ orientations was 65.80 msec/item). Separate ANOVAs of the target-present data and the target-absent data revealed no significant asymmetry effects for either set of data.

An overall ANOVA was performed to compare the orientation tuning function for the shaded displays (Figure 4) with that for the bipartite displays (Figure 6). Overall, the search rates for the shaded displays were faster than those for the bipartite displays [$F(1,162) = 33.95, p < .01$]. Furthermore, a significant three-way interaction between target presence, orientation, and display type was found [$F(8,162) = 2.54, p < .05$]. Display type did not interact with any other factor.

In order to assess where the differences lay between the two display types, simple main effects analyses were performed to examine the effect of display on search rate at each of the nine orientations. All orientations except 0°, 22.5°, and 90° yielded significant differences (all $ps < .01$). The search rates for the remaining three orientations were not significantly different from one another ($p > .05$).

Discussion

The orientation tuning function for the bipartite displays is, overall, qualitatively different from the function for the shaded displays. This finding suggests that the bipartite displays may not have been processed by the same neural mechanisms as those that processed the shaded displays. This is consistent with our previous report concerning an agnostic subject who was able to find shaded disk targets among oppositely shaded distractors, but was unable to use bipartite displays for this type of task (Humphrey, Symons, Herbert, & Goodale, 1996; see also Humphrey et al., 1997).

The present experiment replicated previous findings of similar search rates for both the shaded and bipartite displays in the 0° orientation condition (Aks & Enns, 1992; Kleffner & Ramachandran, 1992). This similarity was extended to the 22.5° and 90° orientation conditions, but not to the remaining orientations. This finding suggests that the luminance step in the bipartite stimuli was not sufficient to generate rapid search rates in a manner similar to that for the shaded disks. Rather, it would appear that there may be some interpretation of depth information necessary for rapid search to occur. It appears that the configuration of dark and black regions on a bipartite disk was not sufficient as a predictor of 3-D properties to drive early visual processes, as was implied by Aks and Enns. It is possible that the few similarities in search rates between the bipartite displays and the shaded

Figure 6. Mean search rates as a function of lighting orientation for the bipartite displays in Experiment 2.

displays were merely coincidental. As such, any similarity in search rates between these two conditions might have limited significance.

EXPERIMENT 3 The Effects of Lighting Direction

Sun and Perona (1996b) reported that, when displays are lit from the upper left, they are processed more quickly than when they are lit from the upper right. In their task, observers were required to detect the presence of a shaded disk target before the onset of a mask. The processing speed was determined by the amount of exposure time needed to detect the presence of the target. This difference in processing as a function of the direction of the light source might explain the large differences in search rates between the 67.5° conditions and the 112.5° conditions in Experiment 1. The 67.5° display was a right-lit ball target among right-lit pock distractors, whereas the 112.5° display was a left-lit pock target among left-lit ball distractors. Thus, the slower search rates for the 67.5° condition might merely have been the result of the rightward-positioned light source.

In Experiment 3, we used a search task to examine responses to the 67.5°, 90°, and 112.5° conditions as a function of the direction of the light source. If the asymmetry between the 67.5° and 112.5° conditions was merely a function of the direction of lighting, then this asymmetry should be reversed if the direction of lighting was reversed. If this asymmetry was due to the depth interpretation (pocks are processed faster than balls; Kleffner

& Ramachandran, 1992), the direction of the light source should have no influence.

Method

Participants. Fourteen observers with normal or corrected-to-normal vision participated in all conditions.

Apparatus. The stimulus presentation and data collection apparatus were identical to those in Experiment 1. Six conditions were presented (see Figure 7). These conditions consisted of shaded disk displays with light sources located at 67.5°, 90°, or 112.5°. Three of the displays had light sources located to the left, and three had light sources located to the right. For the 90° displays, the direction of lighting was arbitrarily defined. With these lighting conditions, the displays could be defined as balls, undefined (the 90° conditions), or as pocks that were right or left lit.

Procedure. Each observer participated in all conditions sequentially in a randomized order. The experimental design within each condition was identical to that of the previous experiments, except that the observers were presented with six blocks of displays of 40 trials per condition.

Results

In the present experiment, we were primarily interested in testing hypotheses concerning the asymmetry in search rates found in Experiment 1, and, for the sake of brevity, only the search rate data will be described. The search rates are shown in Figure 8. As this figure shows, the direction of lighting had no significant influence on search rates. The perceptual interpretation of the display had a strong impact on search rates, however—that is, pocks were processed more quickly, regardless of direction of lighting. These results were confirmed by a $3 \times 2 \times 2$ (lighting orientation $\times$ lighting direction $\times$ target

Figure 7. Examples of target and distractor items used in Experiment 3.

presence) ANOVA. A significant effect of lighting orientation was found [$F(2,26) = 19.495, p < .01$], as well as a significant effect of target presence [$F(1,13) = 15.504, p < .01$] and a significant interaction between lighting orientation and target presence [$F(2,26) = 4.91, p < .05$]. No other significant effects were found.

Discussion

The search asymmetry found in Experiment 1 was more likely the result of differences in the perceptual interpretation of the displays (search rates for pock targets were faster than those for ball targets, Kleffner & Ramachandran, 1992) rather than the result of the effect of the direction of the light source. Contrary to Sun and Perona's (1996b) finding, the direction of lighting had no effect on search rates. In fact, in many cases, the search rates for the left-lit displays were slower than those for the right-lit displays (albeit not significantly). The differences between the search procedure used in our Experiment 3 and the masking procedure used in Sun and Perona's (1996b) study may account for the different outcomes of these two studies.

EXPERIMENT 4

Orientation Tuning and Depth Estimates

Kleffner and Ramachandran (1992) suggested that the rapid search rates associated with shaded disks were the

result of an early derivation of depth information from these displays. Aks and Enns (1992) found that depth estimates of various display types did not correspond well with search rates: 0° bipartite displays evoked little sense of depth, but produced reasonably fast search rates (see Experiment 2 for some limitations to this argument). They concluded that depth information, per se, is not a necessary precondition for rapid search of these displays. Berbaum, Tharp, and Mroczek (1983), who used a binocular rangefinder (Gregory, 1966), found that the position of a light source affected the impression of depth in grayscale photographs of balls. In particular, top-lit shaded photographs generated a greater impression of depth than did side-lit shaded photographs. These data show an interesting parallel to the search rates described in Experiment 1—that is, faster search rates appear to be associated with a greater sense of depth.

In Experiment 1, we found variations in search rates with orientation of lighting. In Experiment 4, we examined how these variations might be related to the phenomenological sense of depth created by shaded disks. Magnitude estimates of depth were measured as a function of lighting orientation.

Method

Participants. The participants consisted of 12 experimentally naive volunteers who received course credit for their involvement. All had normal or corrected-to-normal vision.

Apparatus. The apparatus was identical to that used in the previous experiments. The displays were created using target and distractor items from the nine orientation conditions employed in the first study (see Figure 2, left column). Each display consisted of one target and 11 distractors, and the position of the objects did not change across displays (Figure 1 shows the approximate spatial relationship of the items in the displays used in Experiment 4). The nine displays differed only with respect to the orientation of the luminance gradients.

Procedure. The participants were seated in a dark room, 80 cm from the computer screen, and their heads were placed in a headrest with temple stops. The participants were told to imagine the surface of the screen having a depth of 0 and to indicate the degree of depth for the target object in each display. Because some pilot participants had difficulty in assigning a direction of depth for some orientations, the participants were not given instructions concerning direction of depth. Each participant was allowed to use his/her own modulus. The order of display presentation was different for each participant.

Results

The mean depth estimates are presented in Figure 9. As can be seen in the figure, the impression of depth varied as a function of lighting orientation. Depth estimates were highest for the 45° and 135° orientation conditions and lowest for the 67.5° orientation condition. This was confirmed by a significant one-way ANOVA [$F(8,88) = 3.58, p < .01$]. An analysis similar to that used in the first two experiments to assess an asymmetry in depth percepts as a function of target type showed that the $> 90^\circ$ orientation conditions were associated with greater depth estimates than were the $< 90^\circ$ orientation conditions [$F(1,11) = 5.72, p < .05$].

Figure 8. Mean search rates as a function of lighting orientation and direction of lighting for the shaded displays in Experiment 3.

Discussion

The phenomenological impression of depth is related to the orientation of the light source. This relationship bears a crude, complementary relationship to the search-rate orientation tuning function shown in Experiment 1. Although no direct causal link can be inferred from these data, it appears that the greater the impression of depth, the faster the search rates. This appears particularly true for the oblique (45° and 135°) and 67.5° orientations. In Experiment 1, the oblique orientations showed faster (albeit nonsignificant) search rates than did the remaining orientations. In Experiment 4, the oblique orientations were associated with the greatest depth estimates. The estimates of depth showed an asymmetry that was also consistent with the search asymmetry described in Experiment 1.

These depth estimates also show an interesting parallel to a recent report from Sun and Perona (1996b). They found that observers performed best for oblique lighting orientations in a stimulus onset asynchrony masking task. Furthermore, in a survey of 225 paintings in which shading was a depth cue, Sun and Perona (1996b) found that oblique lighting orientations were used in 77% of these paintings. It may be that the relative popularity of oblique lighting orientations in paintings is a result of the increased impression of depth conveyed by this type of shading.

The present data suggest that the early visual mechanisms that are being tapped by the visual search paradigm may be deriving some estimate of the shape of the display items. It might be expected that, if these early visual mechanisms are merely responding to "quick and dirty" predictors of depth, the search rates and magnitude estimates would show little concordance. Presumably, a shaded disk with an oblique luminance gradient should have little more predictive value than would a shaded disk with a 0° luminance gradient. The impression of depth appears to be related to performance in the search task, that is, the greater the depth, the faster the search rates. Thus, previous explanations for search asymmetries of shaded objects may be unwarranted. Rather than being the result of looking for "unexpected" targets (Kleffner & Ramachandran, 1992) or reflectance changes in the object (Sun & Perona, 1996a), the faster search rates for pock targets may merely be due to the greater sense of depth that these display items convey. These data are consistent with a recent report in which Troje and Symons (1998) compared search rates for shaded faces with those for shaded disks. The search asymmetry exhibited for disks did not appear when observers searched for shaded faces. They concluded that, because the bottom-lit faces never

Figure 9. Mean estimates of the magnitude of depth of the target shaded disk as a function of lighting orientation in Experiment 4.

appeared as concave masks, the search asymmetry for the disks was likely due to the depth interpretation that was applied to shaded displays.

GENERAL DISCUSSION

It has been suggested that in deriving shape on the basis of shading gradients the visual system "assumes" that the gradients were produced by light from above (Kleffner & Ramachandran, 1992). Our results show that the visual system is able to make rapid discriminations of a broad range of shading gradients at different orientations, suggesting that the "lighting from above" assumption is broadly tuned. Search rates were rapid for all implied lighting orientations except for those relatively close to horizontal. This is consistent with the view that the derivation of shape from shading information occurs at a fairly low level of the visual system and relies on very general assumptions about the display. This is also consistent with the nature of lighting in the natural world. Most light sources are rarely located directly above our heads. Much of a scene is illuminated not only by a primary light source, but also by light reflected from other surfaces, or even the air. All of these sources combine to broaden the lighting source (although the shading information should have an intensity gradient toward the primary source). Rather than speak of an assumption of overhead lighting in these displays, it may be more accurate to say that our visual system uses an assumption of a unitary light source that usually does not originate from some horizontal orientation (although this description is considerably less convenient).

The use of a range of display types in the present experiments demonstrated the important differences between the bipartite and shaded displays that were previously not evident. Previous works (Aks & Enns, 1992; Kleffner & Ramachandran, 1992), which suggested similar mechanisms, might have analyzed shaded and bipartite displays on the basis of their conclusions on the similarities between the search rates of these displays. However, only two specific cases (the vertically and horizontally lit displays) were examined in these studies. Only when one examines the search rates of a range of intermediate cases do important qualitative differences between these displays arise. The fact that similar search asymmetries are found for the vertically and horizontally lit cases for both shaded and bipartite displays may be merely coincidental. Indeed many search asymmetries have been demonstrated for a wide variety of stimuli, but this does not necessarily imply that these different stimuli are being analyzed by similar mechanisms.

The analysis of shape from shading is very rapid, but may be limited in precision. The phenomenological impression of depth varies as a function of lighting orientation, even though, merely on the basis of the shading characteristics of the objects, there should be no change

in depth. Bülthoff and Mallot (1988) and Todd and Mingolla (1983) also found that depth estimates were not closely related to the nature of shading information in the display. Furthermore, Bülthoff and Mallot found that shading information can be easily vetoed by other, conflicting cues to depth (e.g., stereo). Ramachandran (1988) demonstrated that familiarity information easily overrides shading information; a face shaded from below is never seen as the inside of a mask, which the shading information would imply.

A very general role for shape from shading as a cue to depth might be suggested. The analysis of shading might represent a very primitive first "module" in the analysis of depth information in a scene (e.g., Bülthoff & Mallot, 1988). Similar to occlusion as a cue to depth, it is largely responsible for providing information about the direction of depth. Since lighting in the real world is relatively unconstrained, this module cannot provide very good estimates about the absolute values of depth and thus is somewhat limited in extracting form information. Since shading is a relatively imprecise cue to depth, it would not make sense for the visual system to expend a large amount of effort in attending to shading information. Instead, very general heuristics are used, and the decisions made with this module are easily overturned by other depth modules. Shape from shading might be viewed as a compelling illusion of limited accuracy.

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