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USE OF INTERREFLECTION AND SHADOW FOR SURFACE CONTACT

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ABSTRACT

The interaction of light with surfaces results in a number of lighting effects that may serve as valuable visual cues. Previous research on shadows has shown them to be effective in determining the 3D layout of a scene, but interreflections have been ignored as a cue for spatial layout. The addition of interreflection as well as shadows may help to disambiguate the 3D layout of objects by providing information about object contact with a surface. We generated computer images of a box on an extended textured ground plane that was either in contact with the ground or slightly above the ground. Images were rendered for four conditions: 1) no shadow plus no interreflection, 2) shadow only, 3) interreflection only, and 4) shadow plus interreflection. A photometrically incorrect condition was also included. Participants rated the degree of contact for each image on a scale which was used to generate ROC curves and a measure of sensitivity. In the images with no shadow or interreflections, the participants performed at chance. Interreflections, shadows, and a combination of interreflections and shadows all resulted in a high sensitivity for judging object contact. More importantly information from shadows and interreflections can be combined to result in near-perfect judgement of surface contact. Interreflections and shadows can be effective cues for object contact.

Key Words: spatial layout, interreflection, shadow

INTRODUCTION

In our everyday experience we interact with objects and need to determine their relative positions. Determining the spatial relationships between objects in a scene is important for actions such as path planning, object avoidance, reaching, and grasping. There is a considerable body of knowledge regarding both quantitative and qualitative perception of relative depth between objects (Sedgwick, 1986; Cutting & Vishton, 1995). Quantitative judgments, such as estimation and discrimination, are based on a representation of distance as a continuous variable. Relative judgments of depth can also be qualitative and based on a categorical representation of object relations. An object can be inferred to be “in front of” or “behind” another, without an explicit estimation of metric distance. For example, when one object occludes another the resultant T-junction is a monocular cue for a qualitative depth relationship. The focus of this paper is on another useful, but less studied qualitative judgement, that of deciding whether or not two surfaces are in contact. Contact is useful for deciding if a region is an object or part of an object, or if an object is detachable or graspable. Contact information can also be used to support the estimation of absolute or relative distances both to and between objects. For example, by determining the contact between an object and a homogeneously textured ground plane observers can quite accurately judge the distance to the object (Sinai, Ooi & He, 1998). So what are the cues for contact, and are there any which may be particularly important for contact judgements as distinct from other judgements of relative spatial relationships?

Different pictorial cues can be used for determining contact, primarily by generating reliable depth judgements to different surfaces. Reliable depth judgements rely on image measurements that are correlated well with surface features. Image variation associated with illumination change typically confounds the detection of surface features. Because illumination effects such as shadows, interreflections, and specularities are highly variable and not tied unambiguously to object location, these effects of illumination have historically been considered something to be discounted in studies of shape and depth perception in both human and computer vision. However, the interaction of light with objects results in a number of illumination effects, which may be useful cues for surface attributes and relations. For example, shadows have been found to be useful for determining spatial layout. In children, shadows have been found to be effective in influencing depth and height judgements of an object on a plane (Yonas, Goldsmith & Halstrom, 1978). The displacement between a cast shadow and the casting object in an image grows with the relative depth between two surfaces (Kersten, Knill, Mamassian &Bulthoff, 1996; Kersten, Mamassian &Knill, 1997). This displacement measure is very effective for correctly evaluating the 3D spatial layout of a scene.

(Insert Figure 1 here)

Interreflections are a subtle lighting effect that may also provide information for suface relations. Interreflections are the result of light bouncing between multiple surfaces (figure 1). They are responsible for illuminating areas that are not directly illuminated by the light source. Interreflections also add to the color and luminance reflected by areas receiving both direct and indirect illumination. In trying to create 3D photorealistic computer images, accounting for interreflections has proven to be very important, and has lead to radiosity and ray-tracing rendering techniques in computer graphics (Foley, vanDamme, Feiner & Hughes, 1996).

Interreflections may be important to determining surface contact partially because of their close relationship to shadows. Though they are the result of light transport as opposed to light occlusion, Langer has recently described an insightful relation between the two (Langer, 1999). Consider the intersection of two surfaces. Decreasing the angle between the surfaces also decreases the likelihood for a randomly placed light source to strike either of the surfaces; hence the more likely for there to be a shadow. However, as the angle between the two surfaces decreases, any light source that does enter will result in more bounces between the surfaces, and hence the more likely for there to be interreflection. This close relation to shadows, which are effective in relating spatial layout, suggest interreflections may also be a source of information useful for determining spatial layout.

Interreflections seem to be visually rather subtle. Although shadows can also be subtle effects, they can be quite sharp and salient, such as on a sunny day. Might the greater subtlty of interreflections reduce their effectiveness as a contact cue? Gilchrist & Jacobsen have shown interreflections to be potentially useful (Gilchrist & Jacobsen, 1984). They constructed a world of one reflectance in which observers were able to distinguish a matte white room from a matte black room, even when they were both illuminated so as to have the same average luminance values. The difference was the luminance profile of the room. The matte white room has a higher number of ambient bounces (interreflections) than the matte black room resulting in flatter profile, while the matte black room had a more variable profile. Another study showed that the visual system can discount the effects of interreflection in determining surface color, given 3D knowledge of the surface arrangement (Bloj, Kersten & Hurlbert, 1999). They created a colored "mach" card, one side red the other side white. In the concave condition people were able to discount the pink color-bleeding on the white side which was due to interreflection, thereby seeing the side as primarily white, but with a tinge of pink. In the convex condition the pinkish color was not discounted, and the same surface (previously seen as whitish) was perceived as a magenta-colored, a change in material property. In computer vision, interreflection has also been shown to be useful in algorithms which identify edge discontinuities (Forsyth & Zisserman, 1992; Nayar, Ikeuchi & Kanade, 1991).

Although we have experimental evidence that the visual system is sensitive and can make use of some of the subtle effects of interreflections, are they also useful for judging contact? If so, what is the image information for contact? In order to answer these questions, it is important to dissociate the contributions of cast shadows and interreflections. We measured the ability of observers to reliably judge the contact between two surfaces under conditions for which we could control the contributions of cast shadows and interreflections. Further, we also tested whether a simple geometrical constraint typical of certain types of contact might be important for contact judgments.

METHODS

Computer graphics was used to simulate images of a rectangular box which was either in contact with or slightly above a floor (figure 2).

(Insert Figure 2 here)

The floor was a continuous ground plane with a checkerboard texture. The checkerboard geometry provides strong cues to surface slant, while the reflectance changes create X-junctions that provide additional information for the determination of illumination edges (Adelson, 1993; Knill, Mamassian & Kersten, 1997). Shadows and interreflections were generated by simulating the physics of light transport using a standard Monte Carlo renderer (Thompson, Shirley, Smits, Kersten & Madison, 1998; Kajiya, 1986). Viewpoint was fixed. The scene was illuminated by either one or two light sources. The lights were diffusely illuminating panels with a flat intensity curve. Computed images were quantized to an image with 256 levels per channel, where zero intensity was mapped to the lowest image level, the largest RGB value was mapped to largest image level, and remaining were mapped linearly between these extremes.

The experiment varied three basic conditions; lightsource (one or two), shadow (present or absent) and interreflection (present or absent). Figure 3 represents the 16 basic conditions in gray-level format.

(Insert Figure 3 here)

In order to test whether a simple geometric constraint (discussed below) might be used to determine contact, an additional condition was used in which the image rendering was not based on a realistic model of the physics of light. This “faked” condition had one light source, a white shadow, and a photometrically incorrect (red instead of green) interreflection. (Figure 4)

(Insert Figure 4 here)

In each of the above conditions the scene was rendered twice, with the box slightly above the floor, and with the box touching the floor.

Twenty-two participants viewed each image ten times in a random order. Participants made a judgement in which they ranked their confidence regarding the contact between the floor and the box. The degree of contact choices were: definitely touching, maybe touching, unsure, maybe above, and definitely above. The images were displayed at a resolution of 1024 X 768 on an Applevision 1710AV display at a distance of 64cm. The monitor had a gamma of 1.8 and the images were gamma-corrected to use the standard Macintosh look-up table. The images had a mean luminance of 120 cd/m^2, with shadow areas averaging 15 cd/m^2 and the highly illuminated areas averaging 200 cd/m^2. All participants had normal or corrected to normal vision, gave their informed consent, and received extra credit for their participation in a research experience program connected to a first year psychology class.

DATA ANALYSIS

Participant responses were analyzed independently. Because each image can be considered as having a “correct answer”, either touching or above as determined by the geometry of the 3D model, Receiver Operating Characteristic (ROC) curves could be generated for each individual, for each condition. The ROC curve represents a graph of hits vs. false alarms for various criterion levels. The ROC can be generated by determining the correct number of responses for each criterion level (definitely touching, maybe touching, unsure, maybe above, and definitely above), and plotting hits (object is touching and participant says it is touching) against false alarms (object is not touching and participant says it is touching) (Green & Swets, 1974). The area under the ROC curve provides a measure of sensitivity and ranges from 0.5 (chance) to 1 (perfect). Our summary measure of contact was z-score of the area under the ROC curve[1].

RESULTS

(Insert Figure 5 here)

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[1] The zscore of the area is proportional to a d’, a standard measure of sensitivity. Specifically, the area under the ROC curve equals the predicted proportion correct in a two-alternative forced-choice experiment, assuming equal-variance gaussian distributions on the underlying decision variable.

Figure 5 shows the calculated sensitivity for one-light and two-light conditions, error bars were calculated by bootstrapping the original data (Efron & Tibshirani, 1998). In the one-light condition subjects were significantly better at discriminating contact using shadow information as compared to interreflection information. However in the two-light condition performance in the shadow and interreflection conditions were not significantly different. Subjects did worse with two-light-source shadows than with one-light-source shadows, however they did better with two-light-source interreflections, than single-light-source interrreflections. In both the one-light source and two-light source conditions the combination of shadow and interreflection results in the highest sensitivity to contact. This sensitivity is significantly greater in the shadow + interrreflection condition, than in either condition alone. A natural question to ask is if this improvement in sensitivity is due to probability summation or information summation.

Probability Summation

Probability summation is described by the summation of two detectors output of the independently analyzed signals, and is computed using the following equations:

$$\text{Hits: } 1 - (1 - P_{hitS})(1 - P_{hitI})$$

where,

P_{hitS} is the probability of hit for shadow condition, and

P_{hitI} is the probability of hit for the interreflection condition, and

$$\text{False Alarms: } 1 - (1 - P_{faS})(1 - P_{faI})$$

P_{faS} is the probability of false alarm for shadow condition, and

P_{faI} is the probability of false alarm for the interreflection condition.

Once the probability summation hits and false alarms are calculated, they can be used to generate a ROC curve, which is used to calculate the predicted sensitivity (z-score of the area) to a combination of shadow and interreflection. This resultant estimate of sensitivity using probability summation is plotted in figure 5.

Information Summation

Information summation combines information from two independent sources more efficiently than probability summation. Estimated performance on the shadow + interreflection condition is calculated using the following equation:

$$d_{sum}' = \sqrt{((d_1')^2 + (d_2')^2)}$$

d_1' is the sensitivity measure for one condition (i.e. shadow)

d_2' is the sensitivity measure for a second condition (i.e. interreflection)

The predicted sensitivity due to information summation (d_{sum}') is plotted in figure 5. The sample data falls right between the predicted sensitivity values from probability summation and information summation.

Due to the ceiling on probability summation, and the large number of participants in this study who showed perfect sensitivity in the task using just shadows or just interreflections (called “experts”), the data was split into expert and non-expert groups. In the one-light-source condition there were 5 shadow experts, 2 interreflection experts, and 9 shadow + interreflection experts. In the two-light-source condition there was 1 shadow expert, 5 interreflection experts, and 11 shadow + interreflection experts. These groups were reanalyzed to see if experts might be combining the information from the stimuli in a different manner than the non-experts. Resampling the raw rating data using a bootstrap technique (Efron & Tibshirani, 1998) provided statistical support for the conclusion that participants who showed perfect sensitivity in the task using just shadows or just interreflections, just by chance, would be extremely rare ($p < .005$). An important point to note is that in both the one-light and two-light conditions, the combination of shadows with interrreflections resulted in a higher number of experts than with shadow or interreflection alone. However, analysis suggests the experts did not combine the information from the stimuli in a different manner than the non-experts.

Faked Images

Analysis of the faked-image condition shows that sensitivity for contact with white shadows and photometrically incorrect interreflections was less than either the photometrically correct shadow-only or interreflection-only conditions. However, performance was still well above chance (figure 5). Though participants were given contradictory photometric information, what information might be available for making the contact decision?

Image Analysis

The images were analyzed to investigate possible geometrical cues that may be useful for a contact decision. An analysis of the isophotes, or lines of continuous luminance, showed a potential geometrical cue (figure 6).

(Insert figure 6 here)

In the touching condition the isophotes of the interreflection all have a coincidental alignment at the corner of the box. This was also true for the edge of the shadow. However, in condition where the box was slightly above the floor, there was no coincidental alignment.

DISCUSSION

It is important to note that in the case of no shadows or interreflections, performance for determining object contact was at chance. This suggests that in this task participants did not have biased judgements resulting from the effect of other cues, (such as co-planarity with the floor plane). Adding just shadows or just interreflections resulted in a higher sensitivity to object contact. The decrease in sensitivity for discrimination with two-light-source shadows may be due to the coincidental alignment of the shadows, which may result in interpreting the shadows as a pigment change or a rug and not an illumination effect. Improvement in the two-light-source interreflection condition may be due to increased geometrical cues to contact, as is addressed in the image analysis section of this paper. The combination of shadows with interreflections resulted in the highest sensitivity and was significantly greater than in images that had only shadows or only interreflections. Though analysis of the data does not clearly point to probability summation or information summation, it is clear that there is some form of cue combination occurring in the participants. This combined effect of shadows and interrreflections results in much higher sensitivity to contact, suggesting the importance of shadows and interreflection in making subjective contact decisions.

The “faked” condition, which combined shadow and interreflection resulted in a relatively high sensitivity to contact. Though the illumination effects were not physically correct subjects could still make an accurate response, however sensitivity was much worse than for the photometrically correct shadow-only and interreflection-only conditions. Image analysis provides one potentially useful cue in the geometry of the isophotes. The alignment of the shadow and or the interreflection at the corner of the box may provide some information for the decision contact. However, the most accurate judgement did require both photometrically correct shadow and interreflection, suggesting that agreement of all the cue information lead to the best judgement.

CONCLUSION

Though shadows have generally been assumed to be a cue for contact, this research validates this assumption and also introduces interreflection as an equally important cue for object contact. Though interreflections appear subtler than shadows in the image, under the conditions of this experiment, they convey equally strong information about object contact. However, the greatest sensitivity results from a combination of both shadows and interreflections. When taken together, shadows and interreflection prove to be valuable cues to contact and therefor also for spatial layout. This study provides support to the growing importance of considering illumination effects in investigation of human visual perception of spatial layout.

ACKNOWLEDGMENTS

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FIGURES

Figure 1: Interreflection: The dashed line shows direct reflection from a surface. The solid line shows the addition of light bouncing from a nearby object.

Figure 2: Geometry of the Scene: The green rectangle is centered at the origin. Light 1 is centered at (-4.0, 2.25, 12.0). Light 2 is centered at (1.0, 2.25, -12.0). Both lights are 1.5 units by 1.5 units. In the touching condition the rectangle lies on the floor plane (y=0). In the above condition it is 0.010 units above the floor plane. All measurements are in absolute units.

Figure 3:Images used in the experiment: Gray-level versions of images used in the experiments. The original images are on the following web site: http://vision.psych.umn.edu/www/people/cindee/glueimages.html

Figure 4: Faked images: Gray-level versions. These images had the wrong color interreflection (red instead of green) and the wrong polarity shadow (white instead of black). The original images are on the following web site: http://vision.psych.umn.edu/www/people/cindee/glueimages.html

Figure 5: Sensitivity Measures for each condition: The light bars are for the one-light condition. The medium bars for the two-light condition. Darkest bars represent the faked condition (white shadows and photometrically incorrect interreflections). Sensitivity is measured in z-score of area under the ROC curve (note 0.0 is chance). Error bars were calculated using bootstrap analysis. Predicted performance in the shadow + interreflection based on probability summation (circle) and information summation (square) are plotted with the actual shadow + interreflection data. NS NI = no shadow, no interreflection; S only = shadow only; I only = interreflection only; S + I = shadow plus interreflection.

Figure 6: Image analysis; one-light source: Isophotes are lines of continuous luminance, and include interreflection isophotes, shadow isophotes and shading isophotes.

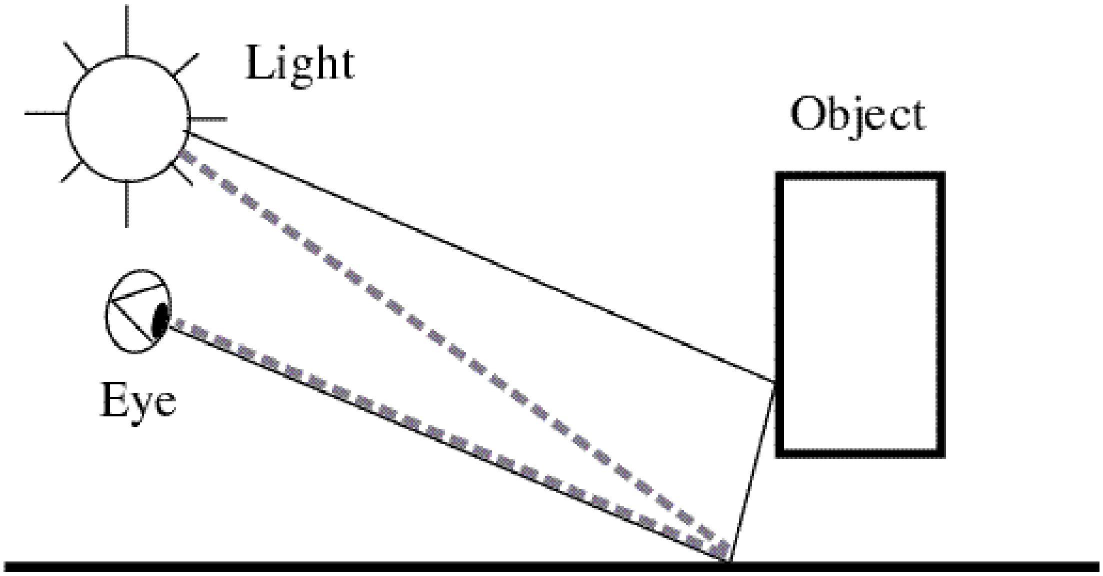


Figure 1

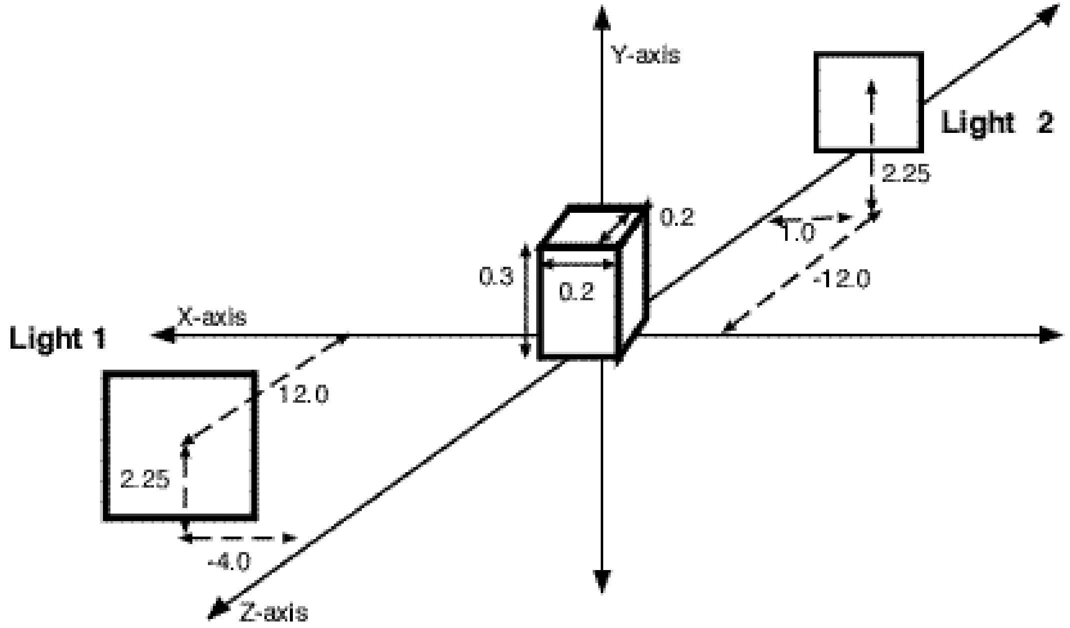
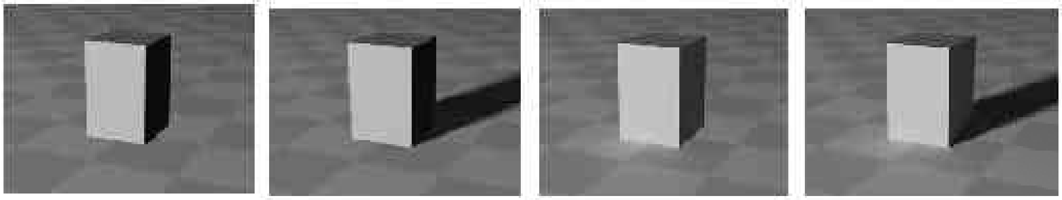


Figure 2

One-Light Source



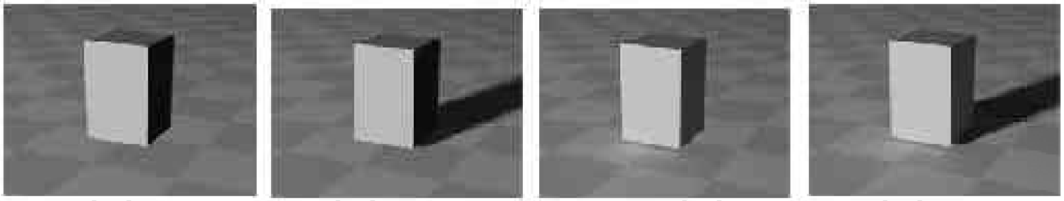
No Shadow No Interreflection

Shadow No Interreflection

No Shadow Interreflection

Shadow Interreflection

Touching



No Shadow No Interreflection

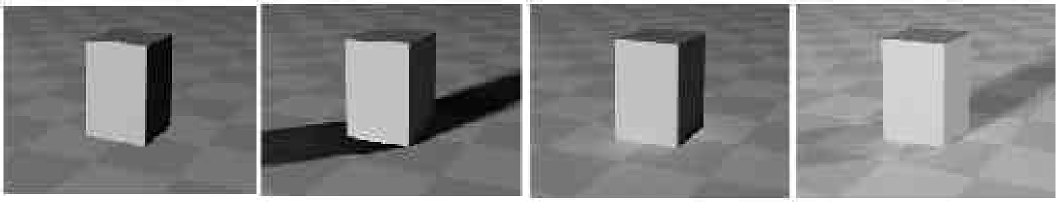
Shadow No Interreflection

No Shadow Interreflection

Shadow Interreflection

Above

Two-Light Source



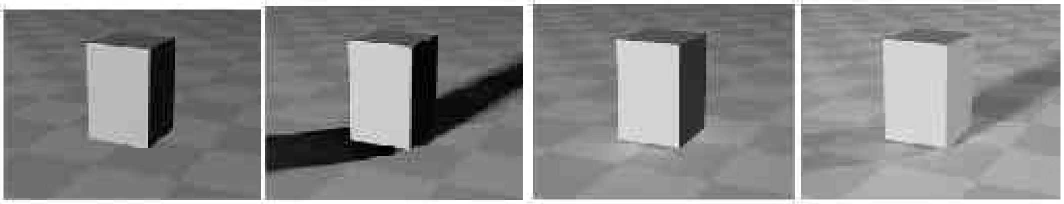
No Shadow No Interreflection

Shadow No Interreflection

No Shadow Interreflection

Shadow Interreflection

Touching



No Shadow No Interreflection

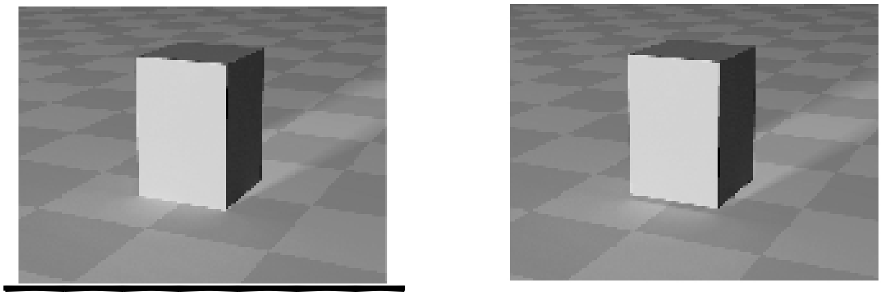
Shadow No Interreflection

No Shadow Interreflection

Shadow Interreflection

Above

Figure 3



White Shadow
Red Interreflection
Touching

White Shadow
Red Interreflection
Above

Figure 4

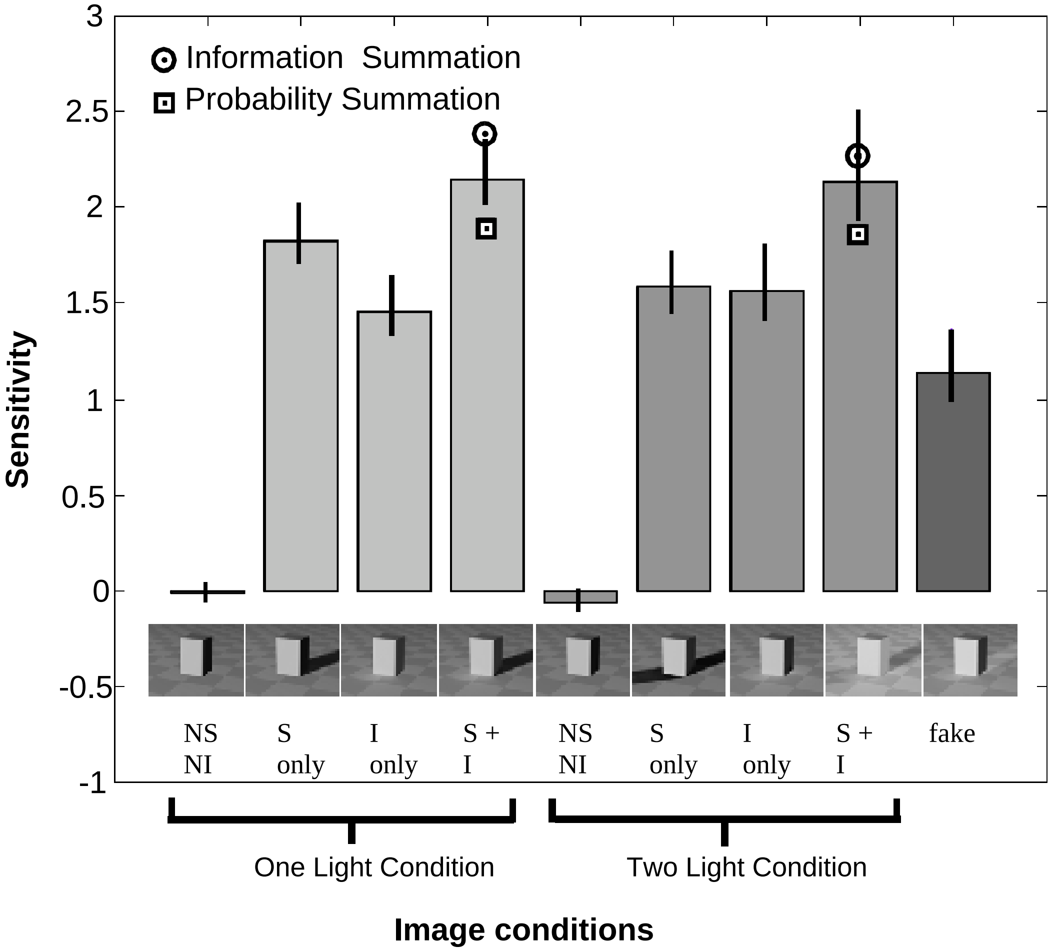

3
2.5
2
1.5
1
0.5
0
-0.5
-1
Sensitivity
Information Summation
Probability Summation
NS NI
S only
I only
S + I
NS NI
S only
I only
S + I
fake
One Light Condition
Two Light Condition
Image conditions

Figure 5

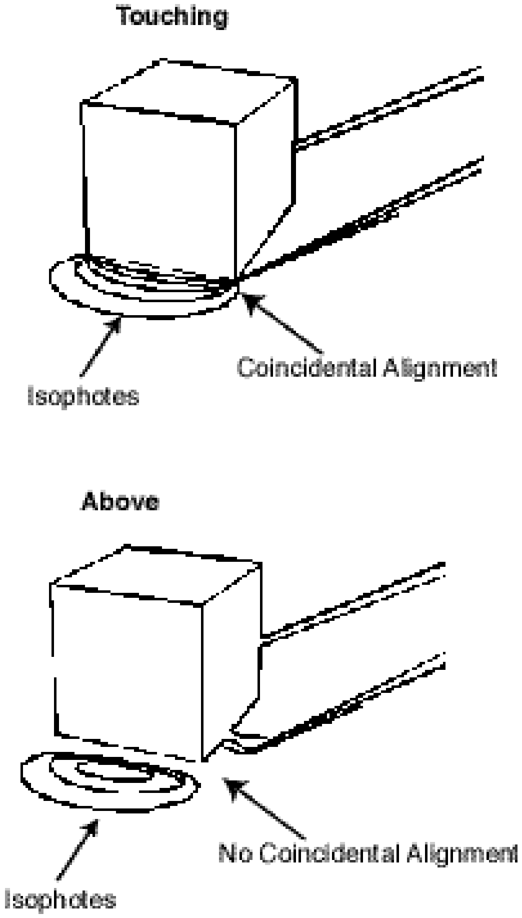

Touching
Coincidental Alignment
Isophotes
Above
No Coincidental Alignment
Isophotes

Figure 6