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**The Suitability of Simplified Cast Shadows as a Visual Depth Cue for
Computer Graphics Applications**

Frank L. Wimmer

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirement for the degree of
Doctor of Philosophy**

**Department of Psychology
Carleton University
Ottawa, Ontario.**

Running head: SIMPLIFIED CAST SHADOWS FOR COMPUTER GRAPHICS

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Computer Graphics Applications"
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Frank Wimmer, B.A., M.A.

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Abstract

Cast shadows provide important information about the elevation and proximity of objects in a pictorial display. Because of excessive computational expense, however, cast shadows are frequently omitted from computer graphics. To evaluate the possibility that the excessive computational demands of displaying cast shadows could be reduced by simplifying the shape of the shadows, five experiments examined the effectiveness of simplified cast shadows. Experiment 1 investigated the impact of various shadow shapes on the apparent elevation of objects. Experiment 2 examined the ability of subjects to discriminate the accuracy of shadow shapes. Experiment 3 compared the accuracy of spatial location judgments based on correct and incorrect shadow shapes. The results of these experiments suggest that simplified shadow shapes were as effective as cast shadows, even though subjects were aware of the inaccuracies between objects and shadows. Furthermore, object location estimates were equally accurate, regardless of whether an accurate or a simplified shadow shape was presented beneath an object.

Two additional experiments examined visual features that might influence the association of a shadow with an object. Experiment 4 examined the role of luminance contrast in associating a cast shadow with an object. Bright and dark shadow shapes were equally effective in altering the apparent elevation of objects. Experiment 5 investigated the role of shadow shape and object-shadow separation distance in the association of a shadow with an object. In the presence of multiple shadow candidates, shape similarity between object and shadow increased the association of a shadow with an object. The separation distance between an object and shadow also affected the association of a shadow with an object.

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Introduction

When viewing a natural scene, a rich set of visual depth cues provide information about the spatial relationships among objects. In contrast, when viewing a two-dimensional display, only a sub-set of visual cues, known as pictorial depth cues, remain to describe the spatial relationships among objects. Research suggests that cast shadows may be the most important cue available for providing information about spatial relationships on two-dimensional surfaces, such as computer monitors (Wanger, Ferwerda, & Greenberg, 1992). Unfortunately, because of the computational difficulty of depicting cast shadows, they are rarely implemented in interactive computer graphics. This thesis explored the potential for simplified cast shadows as a visual depth cue for interactive computer graphics displays. By reducing the visual complexity of cast shadows, the computational complexity can be decreased, thus making cast shadows more feasible for interactive graphics applications. The use of simplified cast shadows could be highly beneficial to users of interactive graphics, such as computer-aided design (CAD), simulations (e.g., flight training and architectural walk-throughs), and virtual reality applications. However, before simplified cast shadows can be recommended for use in interactive computer graphics, two issues must be addressed. First, the dimensions along which cast shadows might be simplified need to be identified. Second, the potential perceptual costs of viewing inaccurate cast shadows in computer graphics applications must be determined.

Overview of pictorial depth cues

Renaissance artists, particularly Leonardo da Vinci, have been credited with the discovery of most of our knowledge of pictorial depth cues (e.g., Kaufman, 1974). The pioneering work of da Vinci and other Renaissance artists in the 1600s resulted in a revolution in the visual realism of paintings. In fact, da Vinci has been credited with

identifying most of the pictorial depth cues that are known today, including linear perspective, shading, and shadow (Woodworth, 1938). The knowledge and use of these cues during the Renaissance era resulted in paintings on flat surfaces that convincingly depicted three-dimensional space.

Among the pictorial cues which result in the perception of increased visual realism, some of the most frequently noted are linear perspective, retinal image size, object occlusion, elevation, shading and cast shadows. Linear perspective is the principle whereby parallel edges of objects appear to converge, and eventually vanish, at a point in the distance. Retinal image size, or relative size, refers to the decrease in the apparent size of an object as the distance between the viewer and object are increased. Object occlusion, or interposition, occurs when an object obstructs the view of another object, resulting in the obstructing object appearing nearer. Elevation refers to the tendency of objects on a ground plane to appear higher in the visual field as their distance from the viewer increases. Shading, the result of different amounts of light falling on an object's surface, provides information about the form of an object. Shadows cast by an object on the surface of another object provide information about the proximity and elevation of those objects, relative to the shadowed surface, as well as further definition of the shape of the object casting the shadow.

For our purposes, it is necessary to distinguish between the cues of shading and cast shadows. Psychologists have occasionally used the term "shadows" to refer collectively to both shading and cast shadows (e.g., Bruce & Green, 1990; Ramachandran, 1988). The two cues are different, however, with each providing unique information about visual depth. Shading refers to the lighting variations on an object's surfaces, as a result of different orientations of the object's surfaces relative to the light source. Cast shadows refer to the reduced illumination on a surface when an object intercepts the light falling on that surface. Shading provides information about the shape of an object, but not about that object's position in space or its relation to its surroundings. Cast shadows, on

the other hand, provide information about the object's position in space and its relationship to other objects. Under some conditions, cast shadows can also provide supplementary information about the shadowed surface and the shape of the casting object. When the more general term "shadow" is used in this thesis, it should be understood to denote cast shadows.

According to cue theories of Bruno and Cutting (1988) and Massaro (1988), visual depth is inferred from the many potential cues available to the viewer. In general, while depth cues are often redundant, a reduction in the available cues increases the potential for misinterpretation of the image. In the case of flat, two-dimensional images, such as computer displays, binocular depth cues such as stereopsis and convergence are unavailable. As a result, only pictorial depth cues remain to describe spatial relationships in the image. Because shading is ineffective in describing relationships among separate objects, the relationship among objects in a static image is dependent on the remaining cues of linear perspective, retinal image size, object occlusion, elevation and cast shadows.

Effectiveness of cast shadows

Cast shadows appear to be a particularly important cue for representing depth on flat, two-dimensional displays. Kaufman (1974) noted that "a picture may look very flat; yet if some shadow is added, it may spring into lively depth" (p. 227). Although Kaufman did not empirically examine the value of cast shadows as a depth cue, research has since supported Kaufman's observation.

Rock, Wheeler, Shallo, and Rotunda (1982) investigated the effects of shading and cast shadows by presenting subjects with a scene constructed only of paper of varying shades of gray to represent shading and shadows. These papers were cut and assembled, then placed on a wall to depict a scene of three cubes resting on a table. When viewed monocularly, subjects believed that they were viewing a real table with three cubes resting on top. In this case, cast shadows (and shading) effectively depicted a three-dimensional scene on a two-dimensional surface.

In research examining the effects of cast shadows on viewers' perception of object location, Yonas, Goldsmith, and Hallstrom (1978) demonstrated that a cast shadow offers two critical pieces of information about an object: proximity from the viewer and elevation above the shadowed surface. When groups of subjects were asked to make judgments about the proximity and elevation of a sphere, trials with the greatest separation between the sphere and its cast shadow were perceived to be the most elevated and the nearest to the viewer. Interestingly, viewers appeared to rely almost entirely on cast shadows in determining the spatial location of the casting object, since the object's relative size (another cue for object proximity) had little bearing on proximity judgments.

The importance of cast shadows for depicting object elevation was also reiterated in research by Kersten, Mamassian, and Knill (1992). Kersten et al. concluded that the distance between an object and its cast shadow provides information about the distance between the object and the shadowed surface. In addition, the perceived trajectory of a moving object was affected by the object's relationship with the cast shadow. When cast shadows were used in dynamic displays, movements of the cast shadows resulted in perceptions of object motion. For example, an animated scene of an object moving along a straight line was perceived as moving along a curved trajectory when only the path of the cast shadow was curved. Likewise, an image of a stationary sphere was perceived as a bouncing ball when only its cast shadow oscillated.

If there are no cast shadows in a pictorial image, the elevation of the casting object must be inferred by the distance of objects above a horizon line. Such inferences are difficult, due to the visual ambiguity resulting from the lack of cast shadows. For example, Figure 1 shows two spheres floating above a horizon. The determination of the relative elevation of the two spheres is ambiguous. While it might be assumed that the two spheres are equally elevated, it is possible that one of the two spheres is more proximal to the viewer than the second sphere. Furthermore, depending upon the relative proximity of the spheres, it is also possible that the sphere on the left is more elevated

above the ground surface than the sphere on the right, or that the sphere on the right is more elevated. By comparison, the spheres in Figure 2 are identical to the spheres in Figure 1, but with the addition of cast shadows. As a result of these cast shadows, the ambiguity about the relative position of the two objects is removed, so that the sphere on the right appears more distant and less elevated than the sphere on the left.

Figure 1. Two elevated spheres.

Figure 2. Two elevated spheres, with cast shadows.

As the figures above demonstrate, cast shadows reduce visual ambiguity about the location of the objects casting the shadows. Under normal circumstances, however, cast

shadows are not as well defined as the idealized shadows shown in the previous figures, but vary in three different qualities. These qualities, shadow sharpness, shape, and luminance, determine the visual quality of cast shadows. The sensitivity of observers to variations in these three shadow qualities will determine how critical each of these components are for incorporating cast shadows in computer graphics applications.

Shadow Sharpness

In the natural environment, cast shadows frequently appear "fuzzy" around the edges. Such cast shadows, sometimes referred to as soft shadows, appear unfocused as a result of illumination by light rays which are not parallel (Kaufman, 1974). As a consequence, various areas of the shadow region are struck by differing numbers of light rays. The darkest region near the center of the shadow, the umbra, is the area where the least amount of light reaches the surface. The fuzziness around the edges of a shadow, the penumbra, is the result of relatively more light rays reaching the surface. The penumbra becomes more apparent when lighting is more diffuse. Lighting is made more diffuse by increasing the size of the light, decreasing the distance of the light from the illuminated object, or increasing the number of light sources. Under diffuse lighting, shadows are softened and become less apparent. Conversely, as a light source becomes smaller and more distant, light rays are more parallel, diminishing the penumbra. As the penumbra is decreased, the contours of the shadow become more defined, resulting in sharp shadows, known as hard shadows.

Only one study has investigated the effects of shadow sharpness on the spatial perception of objects. Wanger (1992) investigated the use of hard and soft shadows on judgments of object location. The study revealed that hard and soft shadows were equally effective cues for determining the proximity and elevation of an object. Subjects viewed a computer display of objects that were located within a "virtual room." Lines on the front and rear floor of the room allowed subjects to estimate object proximity. Similarly, lines on the rear wall of the room allowed subjects to estimate the elevation of

the object. Subjects were asked to give coordinates indicating the proximity and elevation (horizontal and vertical position) of the object inside the virtual room. Results of this research indicated that subjects were equally accurate in judging the location of objects with either soft shadows or hard shadows. As Wanger pointed out, however, hard cast shadows are computationally less demanding to create in computer graphics than soft cast shadows. Because a major purpose of this thesis is to examine the effectiveness of visual information provided by simplified cast shadows (i.e., those feasible on a desktop computer), only hard shadows will be used in the experiments for this thesis.

Shadow Shape

In the natural visual environment, the similarity in shape between an object and its cast shadow is determined by a number of factors. These factors include the position of the illuminating light source and the contours of the shadowed surface. For example, when a light source is positioned at an oblique angle to the object, the cast shadow becomes more distorted, casting an elongated shadow on the ground surface. When the shadowed surface is irregular, the cast shadow follows the contours of that surface and corresponds less to the shape of the object.

A critical factor in determining the similarity of shape between an object and its cast shadow is the angle from which the object is viewed. An object viewed from one side, a foreshortened view, reveals little information about the shape of that object. When an object is depicted in a foreshortened view, a shadow cast by that object will not correspond closely to the shape of the object. For example, a cylinder that is positioned parallel to the shadowed surface and viewed from an end will appear to the viewer as a circular disk. If the object is elevated above the ground surface and illuminated from above, the cylinder will cast a rectangular shadow on the ground. In this case, the shape of the object and its shadow are conflicting: a circular disk (object) and a rectangle (shadow).

Similarly, when an object is viewed from the canonical, or "best" view, the shape of the object may be apparent, however, the shape of the shadow that is cast by the object may not correspond closely to the shape of the object. This may happen if the shadow captures a foreshortened view of the object. In general, the potential mismatches in shape between an object and its cast shadow resulting from viewpoint, lighting direction, and from surface slant and curvature, suggest that correspondence between object shape and shadow shape is not a critical feature for shadows. Even when it is distorted, the cast shadow can still provide information necessary for determining the elevation and proximity of the object. This suggests that a simplified cast shadow shape, one that does not correspond in shape to the shape of the casting object, can serve as an effective cue for elevation and proximity. Alternatively, the possibility remains that under some circumstances, the obvious mismatch between the object and shadow shape could result in the shadow being rejected by the viewer. The outcome depends upon how sensitive viewers are to violations in shadow shape.

Yonas, Goldsmith and Hallstrom (1978) found that observers were insensitive to some information associated with cast shadows. For example, viewers were insensitive to information provided by cast shadows that suggested the direction of lighting. Based on his research into spatial perception as a consequence of cast shadows, Yonas (1979) posed the following questions, "How finely tuned is the perceptual process that responds to cast shadows? If an object casts a shadow that is inconsistent with the shape of the object - for example, if a sphere casts a rectangular shadow - is this immediately detected?" (pp. 108-109). This question may hold an answer for the application of cast shadows to graphic displays on desktop computers. It is possible that a simplified cast shadow that is inconsistent with the shape of the casting object, may still be associated with that object.

The focus of the present thesis is to examine whether cast shadows that are clearly conflicting in shape from the casting object will still be associated with the object

and continue to provide information about object elevation and proximity. Under conditions where the shape of the shadow and the shape of the object are discrepant there are two possibilities. One possibility is that the shadow may be associated with the object and influence the perceived elevation and proximity of the object. The other possibility is that shadow would not be associated with the object and would not influence the perceived elevation and proximity of the object. For example, when viewing an image of a sphere (e.g., Figure 1) the addition of a square shadow beneath the sphere would influence the perceived elevation and proximity of the sphere if the square shadow beneath the sphere were associated with the sphere, but would have no influence if the shadow were not associated with the sphere.

Shadow Luminance

As well as investigating the relationship between shadow shape and object shape, the present thesis will also investigate the role of shadow luminance. In an investigation of shading and shadows, Cavanagh and Leclerc (1989) found that luminance contrast was critical for providing a sense of depth in the object and concluded that in the case of shading, the "shadow" had to be darker than its surround in order to function effectively. The potential shadow could not be lighter than its surround, nor could it be defined using texture, binocular disparity, or motion. Cavanagh and Leclerc proposed that decreased luminance is a defining feature of a shadow in order to describe the spatial position of the object casting the shadow. By extension, it is possible that a cast shadow that is brighter than its surround would fail to be associated with the casting object, thus having no effect on the perceived elevation and proximity of the casting object.

Cast Shadows in Computer Graphics Displays

The information provided by shadows about object elevation and object proximity can be critical for object manipulation tasks on the computer. A study by Wanger, Ferwerda, and Greenberg (1992) varied the cues of elevation, object texture, ground texture, perspective, motion and shadows on three typical computer-aided design tasks.

Of the six depth cues investigated, the cast shadow was found to be the most important cue for two of the three tasks. When cast shadow cues were employed in a positioning task (alignment of one object with two other objects), performance increased in accuracy by 45%. Performance on a scaling task (re-sizing an object to match a second object) improved by 37% when cast shadows were present. Although cast shadows were not the most effective cue for an object orientation task (rotating an object to match the orientation of a second object), performance was enhanced by the inclusion of shadows by 4%. In the presence of cast shadows, performance on all three tasks was superior to performance using only linear perspective or motion cues. This is noteworthy, considering that linear perspective and motion cues (e.g., motion parallax resulting from observer motion) are implemented in interactive computer applications far more frequently than cast shadows.

Friedhoff and Benzon (1989) proposed that the absence of cast shadows from computer graphics is due to their excessive computational expense. They noted that, consequently, the use of cast shadows for interactive computer graphics has usually been reserved for high-end military flight simulators. Herndon et al. (1992) also lamented the high computational demands of rendering shadows in interactive computer applications, stating that an algorithm for creating accurate cast shadows "...can quickly reduce a system to less than interactive speed if even somewhat complex models are being displayed" (p. 5). Recognizing the need to reduce the computational demands of cast shadows for interactive graphic displays, Herndon et al. recommended:

User studies must be performed on all of these techniques, already implemented or proposed, to determine their actual usefulness in real-world applications. It will also be useful to determine to what extent geometry can be omitted before a 3D object and its shadow no longer appear to be related to one another (p. 5).

As Herndon et al. noted, omitting some of the computational demands of cast shadows may make their inclusion in computer graphics applications more feasible. The most computationally demanding aspect of cast shadows is the need to continually calculate their shape, which can be constantly altered in interactive systems by changes in position of the object casting the shadow, the light source, and the shadowed surface. As a result, the most straightforward way to reduce these computational demands is by simplifying the shape of cast shadows. It may be possible to implement acceptable cast shadows that deviate from the correct shadow in shape without incurring the computational demands of accurate cast shadows. The first step in addressing the question of whether inconsistent cast shadows can be effectively implemented in computer systems is to consider the sensitivity of observers to violations in visual depth cues.

Distortions in Visual Depth Cues

Research has indicated that individuals are often unaware of distortions to some visual depth cues. Topper and Simpson (1981) found that viewers were often unaware of distortions to perspective cues of art. Similarly, Yonas, Goldsmith, and Hallstrom (1978) found that viewers ignored information about the location of the light source and simply assumed it to be located overhead, a perceptual anomaly that has been noted elsewhere (Ittleson, 1960; Ramachandran, 1988). This lack of awareness by viewers of some distortions in visual cues suggests that all depth cues need not be processed for spatial judgments. By determining the critical features of cast shadows, it may be possible to remove redundant or unnecessary information, while retaining critical features.

The Present Research

The purpose of the first three experiments was to examine the sensitivity of observers to shape inconsistencies between object forms and their cast shadows. When no cast shadow is present, the location of an object above a ground plane is ambiguous. The addition of a cast shadow decreases the ambiguity by locating the object at a given elevation above the ground plane and at a given distance from the viewer. Thus, as long as a potential cast shadow is attributed to an object, the shadow can provide information about the proximity and elevation of that object. If the shape of a cast shadow is inconsistent with the shape of the object casting it, then it may fail to be associated with that object. However, if the inaccurate shadow shape is associated with the object, the shadow could still provide important location information about the object. Experiment 1 investigated the role of shape correspondence between an object and its cast shadow in affecting changes in the perceived elevation of an object above a ground plane. It was anticipated that shadow shape would play little role in the association of a cast shadow with an object. Thus, the addition of any shadow shape beneath an object should result in a similar perception of object elevation. Experiment 2 examined whether subjects could accurately identify correct cast shadow shapes for objects. It was hypothesized that subjects would be able to accurately identify the correct shadow shape from a set of potential shadow shapes. Experiment 3 evaluated subjects performance in an object localization task. The purpose of this experiment was to assess whether estimates of object location would be accurate when the shape of the shadow does not correspond to the shape of the object. The purpose of the final two experiments of this thesis was to examine additional factors affecting the association of a cast shadow to an object. Experiment 4 examined the role of cast shadow luminance in perceptions of object elevation. It was hypothesized that decreased luminance would be a defining feature of a cast shadow and that shadows that are brighter than the surrounding surface would not be

associated with the object and thus would not affect perceptions of object elevation. Experiment 5 examined the situation where multiple cast shadows were present. By using multiple cast shadows, it was possible to study the relative importance of shape similarity and the separation distance between a shadow and an object in determining the association between a shadow and an object.

For the purposes of the present experiments, three assumptions were made regarding cast shadows. First, in previous research, hard shadows and soft shadows have proven to be equally effective. Consequently, only hard cast shadows, which are less computationally demanding for computer graphics, were used for the present experiments. Second, previous research found that observers ignore information that reveals the location of the light source and assume the light source to be located overhead. Therefore, the shadows for the present research were all positioned directly underneath the casting object. Finally, objects were always displayed in a canonical view, so that shape differences between objects and shadows would be apparent.

Experiment 1

The purpose of Experiment 1 was to examine the influence of cast shadows on viewers' perceptions of an object's elevation. Specifically, the experiment examined how varying the shape of the shadow would affect the perceived elevation of an object above a ground plane. Two questions were addressed. First, does the judged elevation of an object vary with the separation distance between object and shadow when object shape and shadow shape are consistent? Second, does judged elevation vary with separation distance, as it does with appropriate shape, when an inappropriate shadow shape is used?

It was hypothesized that the perception of an object's elevation would be similar in the presence of either a correct or incorrect shadow shape. To address this issue, subjects were first shown an image containing an object without a shadow, followed by an image containing the same object paired with a shadow. This shadow shape was either correct or incorrect for the object in the scene. Subjects were then asked to indicate how much the object in the second image, with a shadow, appeared to differ in elevation from the same object in the first image, without a shadow.

Method

Experimental Design. Four within-subjects independent variables were included: shape of shadows, shape of objects, object-shadow separation, and replications with each test image presented twice. Subjects serving in Experiment 1 also participated in Experiment 2. Half of the subjects first participated in Experiment 1, followed by Experiment 2, while the experiment order of the remaining subjects was reversed. Experiment order was included as a between groups variable. A single dependent measure, apparent elevation change, was recorded.

Subjects. Twenty-four students of introductory psychology at Carleton University participated in Experiments 1 and 2. All subjects reported having some

previous experience using a computer. In return for their participation, subjects were given experimental participation credit necessary to fulfill course requirements of the introductory psychology course.

Materials. The same equipment was used in all experiments. A Macintosh IIvx computer was used to present image stimuli. Images were displayed on an Apple 13 inch RGB color monitor, providing a display resolution of 640 by 480 pixels. An Apple color video card, with a color depth of 16 bits, supplying a palette of 65,536 colors, was used to display images. Two software applications were used for creating images for all experiments: Infini-D ray-tracing/modeling software (Chen, 1993) and Photoshop image editing software (Knoll, 1993). The modeling computations used by Infini-D incorporate the same algorithms used in other commercial modeling and computer-aided design software, rendering images nearing photographic quality (Foley, van Dam, Feiner, & Hughes, 1990; Glassner, 1989).

The stimuli for the experiment were images containing one of four different three-dimensional objects (complex object, cube, torus, sphere) presented on a computer display. A sample image is shown in Appendix A. These four objects were created using the modeling component of the Infini-D software. The computer objects were then rendered as images in the software's ray-tracing module, both with and without cast shadows. All object and shadow shapes for Experiment 1 are shown in Appendix B. All of the shadow shapes were approximately equal in width, but varied slightly in vertical measurement. In addition to the resulting four cast shadows, one additional cast shadow, which will be referred to as the simplified shadow, was created. This simplified shadow was selected on the basis of pilot research which indicated that this shadow was the most acceptable incorrect shadow shape of seven different simplified shadows tested. The simplified shadow was produced by positioning a torus so that its center axis of rotation was parallel to the ground plane, placing a light source directly overhead, and casting a

shadow on the ground. The resulting simplified shadow shape resembles a rectangle with two slightly rounded opposing sides.

As the sample image in Appendix A shows, each image was composed so that one of the four objects appeared in the center of the scene. The object was placed so that its center intersected the horizon in the background. This position was chosen to allow the height of the object above the surface to remain ambiguous; that is, the object could be perceived as either resting on or floating above the surface. In addition to the shadowless image, the second image for each trial contained one of the five cast shadows, located beneath the object. The cast shadow was placed in one of three different vertical separations below the object. These three separations between object and shadow, 2.4 cm, 3.95 cm, and 5.5 cm, were measured from object center to shadow center. In summary, the second image in each trial consisted of one of the four different objects, with one of the five shadows in one of three possible elevations.

Procedure. Each session consisted of 60 comparisons, replicated twice, for a total of 120 trials. In each trial, subjects viewed an image with an object, but no shadow, followed by an image containing the same object with a shadow. To avoid undesirable order effects, 12 different stimulus-presentation orders were created, so that two of the 24 subjects were exposed to each of the stimulus-presentation orders. These 12 stimulus presentation orders were composed of two different replications, with each replication set composed of one of four randomized presentation orders. For each stimulus-presentation order, the combination of four randomized presentation orders, followed by one of the three remaining orders, resulted in the total of 12 different stimulus-presentation orders.

Participants of this experiment also participated in Experiment 2. As a result, experiment order was counterbalanced, so that half of the subjects participated in Experiment 1, followed by Experiment 2. This experiment order was reversed for the remaining subjects. In Experiment 1, as in all of the experiments, subjects sat in front of the computer monitor at a viewing distance of approximately 60 cm.

On each trial, subjects examined the image with a shadow and rated the apparent change in object elevation, relative to the shadowless image. The image without a shadow was presented for a duration of five seconds, followed by an image with a shadow added. The shadowed image, preceded by a brief tone to alert the viewer, was also displayed for five seconds. Following the display of both images, subjects rated any apparent change in elevation of the object in the second image. Subjects marked their ratings on a paper form, shown in Appendix C, containing a scale of continuous ratings from "more elevated," to "less elevated" with a neutral point in the center labeled "equally elevated." This scale was adapted from quality judgment experiments in advanced television research (Stelmach, 1993). Subjects drew a horizontal mark through the position on the scale that they believed most appropriate for rating the degree of apparent change in object elevation. Subjects compared images in this manner for 120 trials.

Results

The main effect of object-shadow separation was statistically significant, Wilk's $\lambda = .59023$, multivariate $F(2, 21) = 7.29$, $p < .005$.¹ Thus the addition of a cast shadow did alter subjects' perceptions of object elevation. Although the object was always displayed in the same screen location, as the separation distance between the object and shadow was increased, the perception of object elevation increased correspondingly. Figure 3 shows the main effect of object-shadow separation. Ratings of elevation change are shown on the vertical axis, with the three object-shadow separation distances shown plotted on the horizontal axis. The small separation (2.4 cm) caused

¹The Mauchly sphericity test was significant in this analysis ($W = .114$, $p < .001$), indicating that assumptions of sphericity were violated and that univariate analyses was not appropriate. As a result, the multivariate analysis of variance was reported. Throughout this thesis, reports of multivariate tests will indicate that the Mauchly test was significant for the analysis. In this event, F approximations to Wilk's λ will be reported. Alternatively, when univariate tests are reported in this thesis, it will be understood that the Mauchly test of sphericity is not significant, in which case univariate F values will be reported.

apparent elevation to decrease, the medium separation had little effect, and the large separation caused the object to appear more elevated, relative to the object with no shadow.

Figure 3. Effect of object-shadow separation on change in perceived elevation.

The shape of the shadow did not affect the perceived change in object elevation. This is demonstrated by a non-significant effect for shadow shape, multivariate $F(4, 19) = 1.045$, $p > .4$, and a non-significant interaction between object-shadow separation and shadow shape, univariate $F(8, 15) = 1.83$, $p > .1$. Figure 4 shows this non-significant interaction between object-shadow separation and shadow shape. Change in perceived elevation is presented on the vertical axis with shadow shape on the horizontal axis. There are separate bars for the three levels of separation. The non-significant interaction indicates that all shadow shapes had similar effects on the perceptions of object elevation.

Figure 4. Change in elevation as a function of shadow shape and separation between object and shadow.

Perceptions of object elevation were not affected by the correctness of the cast shadow shape, as indicated by the non-significant three-way interaction between object-shadow separation, shadow shape, and object shape, univariate $F < 1$. Figures 5 through 8 show the non-significant interaction between object-shadow separation and shadow shape for each of the four object shapes. These graphs show similar perceived change in object elevation regardless of which shadow shape was presented with an object. For example, Figure 5 shows a similar increase in perceived elevation with increased separation for all five shadow shapes when the object casting the shadow was the complex object. Figures 6, 7, and 8 show similar results for the cube, sphere and torus objects, respectively. The non-significant results of this three-way interaction indicate that correct shadow shapes were no better in affecting observers' impressions of object elevation than incorrect cast shadow shapes. As the separation distance between an object and a shadow increased, the perceived elevation of that object also increased, regardless of the shadow paired with the object.

Figure 5. Interaction between object-shadow separation and shadow shape for the complex object.

Figure 6. Interaction between object-shadow separation and shadow shape for cube.

Figure 7. Interaction between object-shadow separation and shadow shape for sphere.

Figure 8. Interaction between object-shadow separation and shadow shape for torus.

Certain objects, on the basis of their shape alone, were perceived as more elevated than other objects. The main effect for objects was statistically significant, multivariate $F(3, 20) = 3.91, p < .03$. The elevation rating of the torus was highest ($M = 54.4$),

followed by the cube ($M = 52$), the sphere ($M = 51.8$) and the complex object ($M = 51.6$). There was a significant interaction of object shape with shadow shape, multivariate $F(12, 11) = 3.48, p < .03$. This can be seen in Figure 9, where change in perceived elevation is shown on the vertical axis with separate categories for object shapes on the horizontal axis. For each object shape, there is a different bar for the five shadow shapes. For example, on the left in Figure 9, the first group of bars shows the perceived elevation change when the complex object shape was paired with the complex, cube, torus, sphere, and simple shadow shapes, respectively. The interaction between object shape and shadow shape is primarily the result of the fact that changes in perceived elevation were generally greater when the object shape and shadow shape corresponded. For example, as shown on the left in Figure 9, the complex object received the highest elevation increase when paired with the complex shadow shape. Similarly, the cube and sphere objects increased the most when paired with their own shadow shapes. The single exception to this was the torus, which was rated essentially the same when paired with the cube, sphere, or torus shadow.

Figure 9. Effect of shadow shape on perceived elevation change for each object shape.

Figure 9 also shows that the effect of the separation between objects and shadows on perceived elevation depended, to some degree, on the similarity between the object and shadow shapes. Elevation changes for the complex and cube objects, which are both angular shapes, were rated highest when paired with either of the complex or cube shadow shapes. Similarly, the torus and sphere objects, which are both rounded shapes, were rated highest when paired with either the torus or sphere shadow shapes. The single exception to this pattern was a high increase for the torus object when paired with the cube shadow shape. In this case, the cube shadow shape, torus shadow shape, and sphere shadow shape all resulted in similar perceptions of increased elevation change.

Figure 9 also shows that there was a relatively small range in elevation ratings for the object-shadow shape combinations. For the 20 combinations of object and shadow shapes, the lowest mean change in elevation was 48.3 for the cube paired with the torus shadow, while the highest was 56.0 for the torus paired with the sphere shadow. The simplified shadow had similar effects on elevation for all objects, ranging in mean changes from 49.9 to 52.2. The perceived elevation change for objects paired with simplified shadows was very similar to elevation change for correctly corresponding object-shadow pairs. It is important to note that, even in the worst case, the greatest difference between an object paired with the correct shadow and the same object paired with the simple shadow was 55.4 versus 49.9 for the cube. In contrast, the least difference between an object with the correct shadow and the same object paired with the simple shadow was 53.3 versus 51.0 for the sphere. It is also interesting to note that elevation ratings for the complex and cube objects varied more in range than the torus and sphere objects. This suggests that shadow shape had less effect on the perceived elevation of the two rounded objects than the two angular objects. As noted above, there was no significant three-way interaction between object shape, shadow shape, and separation. Thus, the pattern of results shown in Figure 9 was obtained for all three levels of separation between objects and shadows.

Significant effects which are not central to this thesis are presented and discussed in Appendix D. MANOVA tables for Experiment 1 (and subsequent experiments) are presented in Appendix E.

Summary and Discussion

The results of Experiment 1 demonstrated that, in a pictorial image, the addition of a cast shadow beneath an object altered the perception of that object's elevation. More specifically, the degree of object elevation perceived was directly related to the separation distance between the object and shadow shape. When a cast shadow was present, increasing its separation distance from the object caused the object to appear more elevated above the shadowed surface. These results converge with previous research on this issue (Yonas, Goldsmith, & Hallstrom, 1978; Kersten, Mamassian, & Knill, 1992). It is not possible, however, to determine the role that either perceptual or cognitive processes played in elevation judgments, on the basis of the present findings.

More importantly, inaccurate cast shadow shapes effectively altered viewers' perceptions of object location. Separation distance between an object and shadow determined an object's perceived elevation, regardless of shadow shape. This suggests that, in spite of incongruities between object and shadow shapes, viewers associated a cast shadow of any shape with the displayed object. On the other hand, although the range in perceived elevation was the same for correct or incorrect shadow shapes, there was a slight trend for objects to appear more elevated when paired with a similar shadow shape. Thus, angular objects were rated as more elevated when paired with an angular cast shadow, while rounded objects were rated as more elevated when paired with a rounded cast shadow. Consequently, although incorrect shadow shapes can be effective depth cues, elevation judgments made with such shadows may be underestimated relative to judgments using correct shadow shapes. It is not possible to address the accuracy of

these judgments with the present experiment. However, this issue is addressed in Experiment 3.

The different shadow shapes had more similar effects on elevation ratings when paired with the sphere and torus objects than when paired with the complex and cube objects. This suggests that the various shadow shapes may have been processed more similarly when paired with the rounded objects than when paired with the angular objects. It is possible that this is due to different visual characteristics between the angular objects and the rounded objects. One visual feature shared by the two angular objects that is not shared by the rounded objects is their visual relationship to the ground plane. Due to the flat bases of the angular objects, it is possible to interpret either the complex or cube object as resting directly on the ground plane, possibly concealing a cast shadow beneath its base. This interpretation is more difficult for the rounded objects, however. Due to the narrower bases of the rounded objects, if the torus or sphere were resting directly on the ground plane, a cast shadow would still be apparent beneath the object. Consequently, it is possible to speculate that the angular objects do not "require" cast shadows as much as the rounded objects. Thus, it is possible that subjects were more compelled to associate any shadow shape with the torus or sphere than with the complex or cube objects.

Experiment 2

The results obtained in Experiment 1 suggest that a variety of shadow shapes can be effective for judging the elevation of an object. Thus, for example, a cube casting a circular shadow appeared to float above the surface. During testing sessions for Experiment 1, a number of subjects offered the observation that the pairing of an object with a shadow of a different shape aided their perception of the object's elevation, even though they were consciously aware that the shadow and object differed in shape. The purpose of Experiment 2 was to examine the ability of subjects to accurately determine

the degree of shape correspondence between object and shadow pairs. The images of objects with shadows from Experiment 1 were used for this experiment. Subjects were shown images containing an object positioned above a cast shadow. Instead of making judgments about the elevation of objects, subjects were asked to rate the possibility that the shadow in the image could have been cast by the object.

Method

Experimental Design. The same experimental design used in Experiment 1 was employed. The dependent measure for this experiment was the estimate of correspondence between object shape and shadow shape.

Subjects. The 24 subjects who participated in Experiment 1 served as participants.

Materials. The computer equipment and images used for this experiment were those used in Experiment 1. The 60 images of objects paired with shadows depicting different elevations were used, while the images of objects without shadows were not used. The rating scale was identical to that used in Experiment 1. The following question was printed at the top of the scale: "How possible is it that this shadow is cast by the object?" The rating scale for this experiment was marked with three labels, ranging from "0%" to "100%" with "50%" placed at the midpoint of the scale. As in Experiment 1, subjects marked their responses at the point on the continuum that best reflected their judgment.

Procedure. Subjects were tested either immediately prior to, or immediately following participation in Experiment 1. Half of the subjects first participated in Experiment 1, while the remaining subjects first participated in Experiment 2.

The training of subjects in the display of the computer images was identical to the procedure used for training subjects to view the images in Experiment 1, with a single exception. Unlike Experiment 1, the display time for each image in Experiment 2 was

determined by the subject. Once an image had been rated, the subject could display the next image in the series by pressing either a button on the keyboard or the button on the computer mouse.

Results

Subjects accurately identified corresponding object and shadow shapes, as indicated by the statistically significant interaction of object shape and shadow shape, multivariate $F(12, 11) = 189.39, p < .001$. Figure 10 shows the mean ratings of correspondence for object and shadow pairings. On the vertical axis, this graph indicates observers' ratings of how possible it was that the shadow shape in a scene could be generated by the displayed object. Shadow shape is shown on the horizontal axis. For each shadow shape, there is a different bar for each object. For example, the leftmost group of bars indicates the judgments of shape correspondence for each of the four objects when paired with the complex shadow shape.

Figure 10. Judgments of object and shadow shape correspondence for all object and shadow pairings.

Figure 10 shows that only shadow shapes paired with their corresponding object shapes received high possibility ratings. Shadows that did not correspond to the object shapes were known to be inaccurate, as reflected by the low ratings. As the rightmost group of bars in Figure 10 show, subjects recognized that the shape of the simplified shadow did not correspond to any of the object shapes. However, the simplified shadow shape received the second highest rating for all objects. The more neutral ratings of the simplified cast shadow suggest that the simplified shadow was an appropriate generic shadow shape for all four test objects.

The results shown in Figure 10 reveal that shape similarities between object and shadow were the critical determinant for identifying correspondence between an object and a shadow. The highest and second highest correspondence ratings for each object were obtained with corresponding shadow shapes and the simplified shadow shape, respectively. The third highest rating for all objects, however, was obtained when similar

shadow shapes were presented (i.e., angular or rounded shapes). For example, the three highest shadow correspondence ratings for the complex object (represented by the black bars in Figure 10) were obtained with the complex shadow, followed by the simplified shadow, and the cube shadow. Similar results are found for the remaining objects, suggesting that subjects were sensitive to similarities between the complex and cube shapes (both angular objects) and between the torus and sphere shapes (both rounded objects).

To investigate the suitability of the simplified shadow as a universal shadow for all four objects, correct pairings of object shapes and shadow shapes were removed from the data. For example, correspondence judgments of the complex shadow paired with the complex object were removed. Judgments including correct shadows with the cube, torus, and sphere were also removed. This organization of the data allowed a comparison of the adequacy of the simplified shadow as a generic shadow to the four remaining shadow shapes. The acceptability of the simplified shadow as an alternative to a correct shadow is apparent in Figure 11 which shows the correspondence ratings of each shadow shape when paired with incorrect object shapes. Correspondence ratings are shown on the vertical axis, with shadow shapes on the horizontal axis. For example, the bar on the left represents the ratings for the complex shadow shape when paired with all incorrect object shapes (i.e., all objects except complex). As the graph shows, correspondence ratings for the simplified shadow are notably higher than ratings for the other four shadow shapes. This suggests that, although all shadows are rated below 40%, subjects were less confident in discounting the simplified shadow shape as a plausible shadow than other shadow shapes.

Figure 11. Ratings of shadow shapes for incorrect objects with effects of correct object-shadow pairings removed.

To examine the relative acceptability of the simplified shadow shape as a universal shadow for the four different objects used in the present experiments, a multivariate analysis of variance was performed on these pairings of non-corresponding object and shadow shapes. For this analysis, the five levels of the shadow independent variable were reduced to two. These two shadow levels were the simplified shadow shape and the remaining data for non-corresponding shadow shapes. The resulting analysis revealed that the effect of shadow shape was statistically significant, univariate $F(1, 22) = 48.22$, $p < .001$.

Object shape also affected judgments of which shadows shapes could plausibly be cast by the objects, multivariate $F(3, 20) = 11.89$, $p < .001$. Figure 12 shows the effects of object shapes on viewers' ratings. Ratings of shape correspondence are plotted on the vertical axis, with object shapes shown on the horizontal axis. For example, the leftmost bar shows ratings of all incorrect shadow shapes (i.e., the cube, torus, sphere, and simplified shadows) when paired with the complex object. Correspondence ratings for the torus were higher than ratings for the remaining three object shapes.

Figure 12. Correspondence ratings for objects paired with incorrect shadow shapes.

With correct object-shadow pairs removed, combinations of object shapes with shadow shapes did not affect ratings of correspondence, as revealed by the non-significant interaction between objects and shadows, multivariate $F(3, 20) = 1.16, p > .3$. Furthermore, none of the interactions involving object shape or shadow shape were significant.

Prior exposure to the material in Experiment 1 did not affect ratings of correspondence between object and shadow shapes. This conclusion is supported by the non-significant effects of experiment order, univariate $F(1, 22) = 2.79, p > .1$, and replications, univariate $F < 1$. Experiment order and replications did not interact with any other independent variables.

Summary and Discussion

The purpose of Experiment 2 was to investigate the ability of subjects to correctly match objects with their correct cast shadows. It was hypothesized that subjects could accurately identify the corresponding shadow from a set of shadow

shapes. The results of Experiment 2 supported this hypothesis, indicating that subjects were able to accurately identify the correct shadow shapes for objects.

Although results showed that subjects were always able to determine the correspondence between a shadow shape and an object, their confidence in these judgments was greater for certain pairings than others. When the shape of the shadow corresponded to the shape of the object, ratings were high, suggesting a large degree of confidence in judgments. Similarly, with the exception of the simplified shadow shape, when an incorrect shadow shape was paired with an object, ratings were consistently low, also indicating confidence in judgments. When the simplified shadow shape was paired with an object, however, it received more neutral ratings than other non-corresponding shadow shapes. This suggests lowered confidence in judgments of objects paired with the simplified shadow shape. This appears to be due to the visual features of the simplified shadow, which shared certain shape characteristics with the objects (containing both angular and rounded contours), making it appear more plausible as a shadow shape than other incorrect shadow shapes. Likewise, other incorrect shadow shapes that shared similar visual features with the displayed object were rated slightly higher than incorrect shadow shapes sharing less visual features. For example, angular shadow shapes (complex and cube) were rated higher when paired with either of the angular objects, while rounded shadow shapes (torus and sphere) were rated higher when paired with either of the rounded objects.

For reasons that are not clear, correspondence ratings of incorrect shadow shapes were higher when paired with the torus, relative to the remaining object shapes. Similarly, correspondence ratings for the sphere object were slightly higher than ratings for the complex and cube objects. Although speculation, these differences could be due to visual features of the object shapes. Due to the flat bases of the angular shapes, subjects may have been predisposed to interpret the complex and cube objects as resting on the surface. For example, if the complex or cube object were positioned on the ground plane, a cast

shadow could be concealed under the object's base. This is not true for the rounded objects. Due to their narrower, rounded bases, the placement of the torus or sphere on the ground surface would result in the object's shadow being visible beneath the object. Because the torus and sphere could not conceal cast shadows, however, subjects may have been less critical of shadow shapes in order to resolve the absence of a shadow from the image.

The high degree of accuracy by subjects in determining correspondence between an object and a shadow is interesting, given the results of Experiment 1. Even though subjects were aware that shadow shapes were often incorrect for objects, they still used the shadows to determine the elevation of the object. It is possible that the shadow shapes in Experiment 1 were highly effective in altering perceptions of object location, in spite of an awareness that object shapes and shadow shapes were conflicting. Alternatively, it is possible that the results of Experiment 1 reveal a tendency of subjects to use any visual information present to interpret an image, regardless of the accuracy of that information.

Experiment 3

The purpose of Experiment 3 was to examine the feasibility of using simplified cast shadows to depict object location in interactive computer graphics applications. Experiment 1 suggested that shape correspondence is not necessary for a cast shadow to be associated with an object. The results of Experiment 1 revealed that viewers experienced similar perceptions of object elevation regardless of whether an object was paired with a correct shadow or a simplified shadow. That experiment, however, examined only the effect of various shadow shapes in altering the relative perception of an object's elevation. The experimental design of Experiment 1 did not allow any conclusions about the accuracy of depth information provided by inaccurate shadow

shapes. Experiment 3 investigated how accurately a simplified cast shadow can convey information about object elevation and object proximity.

It was hypothesized that estimates of object elevation and object proximity using a simplified shadow shape would be as accurate as estimates using a correct shadow shape. To address this issue, subjects were asked to estimate the precise locations of objects using both correct and simplified shadow shapes.

Method

Experimental Design. Four within-subjects independent variables were included in this experiment: shadow shape, object shape, object position, and replication. Subjects serving in Experiment 3 also participated in Experiment 5. The order of participation was counterbalanced between subjects. As a result, experiment order was included as a between groups independent variable. Two dependent measures were recorded: estimates of object elevation and estimates of object proximity to the viewer. To avoid effects due to the presentation order of images, twelve different randomly determined orders of presentation were used.

Subjects. Twenty-four students of introductory psychology at Carleton University participated in Experiment 3. As in previous experiments, all participants reported having previous experience using a computer. For their participation, subjects were given experimental participation credit necessary for requirements of the introductory psychology course.

Materials. The computer equipment was the same as used in earlier experiments. Computer images for this experiment were generated with Infini-D ray-tracing and modeling software (Chen, 1993). In all scenes, a single object was depicted at some distance and height in a "room." Object placement differed only in elevation and proximity, so that the objects did not differ in their lateral position on screen. This computer generated room was composed of two perpendicular planes: a white floor with

a white wall at the back (facing the viewer). Lighting was placed at an apparently infinite distance (200 units) directly above the center of the room. This distance resulted in light rays being calculated at parallel angles to one another, so that cast shadows remained in a stable position relative to its casting object, regardless of object's location in the room. A pair of blue horizontal lines were positioned on the floor; one at the front edge and one on the rear. The front line represented a coordinate value of "0," the rear line a "10."

Similarly, a pair of yellow horizontal lines appeared at the top and bottom of the back wall; the bottom line represented "0," the top "10." Each image contained a single object appearing at some point along these horizontal and vertical planes. A sample image is shown in Appendix F.

To increase the difficulty of location judgments in this experiment, no objects were positioned at the coordinates intersecting or neighboring the horizontal reference lines (i.e., 0, 1, 9, and 10). As a result, each object appeared at one of the 49 central points along the coordinates represented by the horizontal and vertical array. This coordinate system, and the positions used for each object are shown in Figure 13. This figure represents the experimental scene as viewed from the right of the subject's viewpoint. The elevation locations for all objects are shown on the vertical axis, with proximity locations shown on the horizontal axis. The grid in Figure 13 represents the 49 possible locations for objects. For example, the sphere positioned nearest to the subject was located at a proximity of 2 and an elevation of 7. The most distant sphere was located at a proximity of 8 and an elevation of 4.

Four objects were included in the experiment (a complex object, cube, torus and sphere). Each object was rendered in six of the possible 49 spatial locations (determined by the combination of height and distance from the observer), for a total of 24 images. Once these images were rendered with their correct shadows, duplicate images were created with simplified shadows replacing the original shadows for an additional 24 images. These 48 images were randomly ordered and presented in a computerized presentation. Each image was placed in the presentation for a total of 96 trials.

Procedure. Subjects sat in front of the computer monitor at a viewing distance of approximately 60 cm. Prior to testing, subjects were shown a sample image. The sample image depicted a sphere located in the very center of the computer generated room (shown in Appendix F). One of two shadows, either a correct or simplified shadow was shown in the sample image. The two shadows in the sample image were balanced across

subjects, so that half of the participants saw a correct shadow beneath the sphere, while the remaining subjects saw the simplified shadow beneath the sphere. Subjects were informed that the sphere was positioned at "5" along both the horizontal and vertical axes. This sample image was used to familiarize subjects with the horizontal and vertical reference lines. To avoid order effects, 12 different randomly selected stimulus-presentation orders were selected so that two subjects were exposed to each of the stimulus presentation orders.

Subjects were instructed that all objects presented during trials would be positioned at one of seven possible locations, between 2 and 8, along the horizontal axis and at one of seven possible locations, between 2 and 8, along the vertical axis. For each trial, an image was presented on the computer display. The subject was instructed to verbally estimate the position of the object on screen, relative to the blue lines (object proximity). Once this response was recorded by the experimenter, the subject was asked to estimate the position of the object relative to the yellow lines (object elevation). No time constraints were placed on the subject for making these estimates. Once proximity and elevation locations had been estimated for the object, the subject continued with the next trial until all 96 trials were completed.

Results

Error scores were derived from the difference between actual object locations and estimated object locations. The results revealed that object location estimates were equally accurate whether subjects viewed correct shadow shapes or simplified shadow shapes, as indicated by the non-significant main effects of shadows, univariate $F < 1$. Furthermore, shadow shape did not interact with object shape, univariate $F(3, 66) = 2.45$, $p > .07$.

In addition, accuracy of object location estimates were not affected by the object shape, as found by the non-significant main effect for objects, univariate $F(3, 66) = 2.04$,

$p > .1$. Likewise, experiment order and replications had no effect on estimate accuracy, as shown by the non-significant main effects of order, univariate $F < 1$, and replications, univariate $F(1, 22) = 3.67, p > .06$.

Since there were six instances of each object shape and seven possible elevation locations, the position measure represents an ordinal rather than an absolute position. A problem was presented in analyzing the effects of the position variable on location estimates. Because the position variable includes different values for object elevation and object proximity, organization of the data by position resulted in the position variable being correlated with either elevation or proximity. In order to examine the effects of object position on location estimates, the data were analyzed in both ways. First, data were entered with the six levels of position ordered by elevation. Following this analysis, data were also entered with positions ordered by proximity. Results presented above are consistent for both analyses, since this manipulation only affects the outcome of results involving the position variable.

When position was ordered by elevation, so that data was organized from least elevated to most elevated values for objects, position affected the accuracy of location estimates, multivariate $F(5, 110) = 8.99, p < .001$. Figure 14 shows the effect of elevation position of objects on errors in location estimates. The error in location estimate is presented on the vertical axis. The horizontal axis shows the six positions for each of the objects, organized from the least elevated to the most elevated. Each bar represents the ordinal position of objects, relative to the ground. Errors were greater when objects were displayed at their highest and lowest positions. Objects located in the least elevated and most elevated position resulted in the greatest estimate error, while other positions resulted in less.

Figure 14. Errors in object location estimates relative to ordinal elevation positions of objects.

In the second analysis, ordinal position of the objects by proximity affected errors of location estimates, multivariate $F(5, 18) = 12.13, p < .001$. Figure 15 shows the effect of object proximity on errors in location estimates. Errors in location estimates were largest for objects positioned near the viewer ($M = 1.18$). Viewing the graph from left to right shows that as objects were positioned more distant, errors in estimates decreased until the fifth position ($M = .59$), where estimate error was the lowest. In the most distant position, errors increased slightly, relative to estimates of objects in the fifth position.

Figure 15. Errors in object location estimates relative to ordinal proximity positions of objects.

The error results above reflect absolute error, that is the vector distance between the correct location of the object and the estimated location of the object. This is a combination of elevation and proximity error. This approach was selected for statistical analysis, however, since the estimates of proximity and elevation are not independent of one another. That is, a subject must first estimate the elevation of an object in order to estimate its proximity. Figures 14 and 15 can be misleading since the absolute error in an estimate contains error for both elevation and proximity. Because Figures 14 and 15 present the total error in estimate, it does not account for the direction of error.

Figure 16 shows the effect of object position on the separate estimates of object elevation and object proximity, which provides an investigation of elevation and proximity errors independently and indicates the direction of estimate errors (a MANOVA table for this analysis is presented in Appendix G). Thus, Figure 16 displays error means for the actual positions of objects, rather than their ordinal positions. To clarify, each object was located at six different locations along seven possible positions for elevation and seven possible positions for proximity (objects were located between

the positions of 2 and 8 in all images). Figure 16 shows the separate errors for the seven possible elevation positions and the seven possible proximity positions. Error is plotted on the vertical axis, while the horizontal axis on the graph indicates the object locations. The black bars indicate the error in proximity judgments, while the gray bars indicate error in elevation judgments. Positive values on the graph represent over-estimates, while negative values indicate under-estimates. The gray bars on the graph show that observers tended to over-estimate the elevation of objects when objects were positioned nearer. Conversely, object elevation was under-estimated when objects were at the farthest position. The same trend, though less pronounced, is also found for proximity judgments. Finally, the relationship between the black and gray bars shows that, in general, estimates of object elevation were more accurate than estimates of object proximity. Because estimates less than 2 or greater than 8 were not possible, ceiling and floor effects appear to account for some of the estimate error for objects located at the extreme positions. This bias should not have contributed to errors in the more centrally located positions, however.

Figure 16. Independent errors in estimates of object proximity and object elevation for all proximity and elevation positions.

The order in which subjects participated in Experiments 3 and 5 had no bearing on their performance in this experiment, as indicated by the non-significant main effect of experiment order, univariate $F < 1$. In addition, experiment order did not interact with shadows, objects, or replications. The main effect of replications was also non-significant, univariate $F(1, 22) = 3.67, p > .06$, as were interactions with either shadows or objects.

A number of higher order interactions with positions were also significant. These interactions are related to differences due to the random assignment of objects to different positions and are not considered to be important. Graphs for these complex interactions, however, are presented in Appendix H.

Summary and Discussion

The simplified cast shadow was as effective for determining object locations as correct shadow shapes. The present results indicate that, while estimates of object location require cast shadows, it is not necessary for the shape of the shadow to correspond accurately to the shape of the object. Furthermore, subjects appeared to have no difficulty associating the simplified shadow shape with the objects in the scene. In fact, when subjects were informed of the purpose of the experiment during debriefing, several subjects commented that they had not noticed that cast shadow shapes were ever inaccurate.

An examination of errors in location estimates revealed that, regardless of shadow shape, estimates of object elevation were slightly more accurate than estimates of object proximity. For both object elevation and object proximity, however, estimates erred toward the median location. Proximity estimates of the location of near objects were largely over-estimated, while proximity estimates of objects in the most distant position were somewhat under-estimated. Likewise, elevation estimates of the location of low objects were over-estimated, while elevation estimates of objects in the highest position

were somewhat under-estimated. It is possible that this compression of the depicted depth is a result of the linear perspective of the ground floor in the images.

Due to the effects of linear perspective on pictorial images, the apparent distance between objects is inversely related to their proximity from the viewer. Consequently, the distance between proximity locations (from 2 to 8), though equal, would appear more compressed with increased distance from the viewer. For example, if we stand at a set of railroad tracks and look down the tracks, the railroad ties appear to be nearer to one another as they become more distant. In the experimental images, when an object was displayed in the central proximity position (position 5), its shadow marked this position between the two horizontal reference lines on the ground plane. Due to linear perspective, however, this shadow would appear to be closer to the rear reference line than the front reference line. This effect may result in the actual proximity location of the object being over-estimated. This interpretation is consistent with the data, since object proximity was over-estimated for objects located between positions 2 and 7.

Experiment 2 indicated that the simplified shadow shape was the best incorrect shadow shape for the four experimental objects. Consequently, Experiment 3 paired objects with either the correct shadow shape or the simplified shadow shape. As a result, it is not possible to say how accurate object location estimates might be with other incorrect shadow shapes. It is possible that a shadow shape that contains less visual similarity to an object would result in poorer performance on location estimates.

Experiment 4

Cavanagh and Leclerc (1989) suggested that a shadow must be darker than the surface on which it appears for observers to perceive it as a cast shadow. The researchers concluded this from research on shading, however, and the hypothesis has not been tested directly. Thus, the purpose of Experiment 4 was to determine if shadows must be darker than the surround to be associated with an object.

Method

Experimental Design. A total of five within-subjects independent variables were used in this experiment: shadow shape, object shape, object-shadow separation, shadow luminance, and replications. One between-subjects independent variable, groups, was also included. As in Experiment 1, the dependent measure for this experiment was perceived elevation change.

With a few exceptions, the present experiment was identical in method and procedure to Experiment 1. This experiment included 72 trials, consisting of all possible image combinations of two object shapes (complex and sphere objects), three shadow shapes (complex, sphere, and simplified), three object-shadow separation levels (2.4 cm, 3.95 cm, and 5.5 cm), and two luminance levels (negative and positive, relative to the surrounding ground surface). These 36 images were presented twice for a total of 72 trials.

Subjects. Initially, a sample of 12 undergraduate volunteers was recruited for this experiment. Some of the results were uninterpretable relative to the results of pilot testing and Experiment 1. Consequently, a sample consisting of an additional 12 graduate student volunteers was recruited, for a total of 24 participants. The undergraduate students were given experimental credit for their participation, while graduate students were paid \$15. To examine possible differences between the two groups, the two subject samples were analyzed as a between groups independent variable.

Materials. This experiment used the same computer equipment used in earlier experiments. A subset of the images from Experiment 1, which included only images for the sphere and complex objects, was used. Cast shadows for the experiment were limited to the sphere shadow, the complex shadow, and the simplified shadow. To examine luminance as a factor, additional shadows were created which were positively luminant relative to the ground. The contrast polarity of the two shadow luminance levels were

visually adjusted to provide equal contrast from the ground surface. The resulting luminance levels were rated by two judges as appearing equal in contrast from the ground surface. Examples of positive and negative shadow luminances are shown in Appendix I. The possible combinations of independent variables resulted in a total of 72 trials (2 objects, 3 shadows, 3 elevations, 2 luminances, with 2 replications). As in previous experiments, testing sessions consisted of one of 12 presentation orders to avoid order effects. The rating scale used in Experiment 4 was identical to the form used in Experiment 1.

Procedure. Subjects were seated approximately 60 cm from the display. Using the same instructions from Experiments 1 and 2, subjects were briefly trained in the use of the computer presentation software for viewing the on-screen slide show.

Each trial consisted of two images. The first image in each trial, displayed for five seconds, depicted one of the two objects above a ground plane. At the end of the five seconds, a tone sounded to alert the participant of the appearance of the second image. The second image contained the same object shape, with the addition of one of the three shadow shapes, with positive or negative luminance, positioned in one of the three separation distances beneath the object. The second image also appeared for a duration of five seconds. Following presentation of the second image, subjects indicated, by placing a horizontal mark through the rating scale, whether the object appeared to be more elevated, less elevated, or equally elevated relative to the object in the previous image.

Results

Analysis of the data by MANOVA revealed that, consistent with the results of Experiment 1, the main effect of elevation was significant, univariate $F(2, 21) = 71.2, p < .001$. As the separation between the object and potential shadow increased, perceptions of object elevation also increased. Ratings of elevation change were lowest for the small object-shadow separation ($M = 47.5$), followed by the medium separation condition (M

= 59.9), and greatest for the large separation ($M = 68.5$). Because a rating below 50 indicates a decrease in elevation, there was a tendency to perceive objects with shadows in the small separation condition as being slightly decreased in elevation relative to the image of the object with no shadow.

While the results for Experiment 4 generally replicated the results of Experiment 1, the main purpose of this experiment was to examine the possible role of luminance in the association of shadows with objects. Rated elevation change was comparable for positive and negative shadows, univariate $F < 1$. Moreover, there was no significant difference in the perception of elevation changes when positively and negatively luminant shadows were used, as indicated by the non-significant interaction between separation and luminance, univariate $F(2, 44) = 1.04, p > .3$. This indicates that bright shadows were as effective as the dark shadows in affecting perceptions of object elevation at all three separations.

All shadow shapes were equally effective in determining observers' perceptions of object elevation, univariate $F < 1$. Consistent with Experiment 1, the interaction between the object-shadow separation and shadow shape was not significant, univariate $F(4, 88) = 2.14, p > .08$. This finding suggests that shadow shape need not correspond with the shape of the object to be associated with that object and to influence the perceived elevation of the object.

Subjects perceived the elevation change for the two objects differently in this experiment. The main effect of objects was statistically significant, univariate $F(1, 22) = 17.68, p < .001$. There was a higher mean elevation change for the complex object ($M = 61.3$) than for the sphere ($M = 56.0$). The interaction between object shape and object-shadow separation was statistically significant, univariate $F(2, 44) = 4.78, p < .02$. Figure 17 shows the mean ratings for the two objects at each separation level. This graph shows that the tendency of subjects to rate the complex object as more elevated than the sphere

object was larger for the two smaller separation distances between the object and shadow (i.e., separations of 2.4 cm and 3.95 cm) than for the larger separation (5.5 cm).

Figure 17. Interaction between object and separations.

A number of interactions were significant, but were non-systematic and, thus, not interpretable. These results are presented and described in Appendix J.

Summary and Discussion

The purpose of Experiment 4 was to examine the role of luminance in associating cast shadows with objects. It was hypothesized that a cast shadow must appear darker than the shadowed surface to function effectively as a shadow. The results of this experiment, however, did not support the hypothesis. In fact, when a bright shadow shape was placed beneath an object, it functioned as effectively as a dark cast shadow. This suggests that luminance contrast of either polarity may cause a shape to be perceived as a shadow. The levels of shadow luminance did have differential effects on elevation change ratings when interacting with object shape, and with object and shadow shapes. In these cases, however, the resulting trends in ratings were non-systematic.

This suggests that the addition of positive luminance may have resulted in unstable perceptions or unsystematic response biases.

Although speculation, it is possible that subjects interpreted the shadow shapes in Experiment 4 as surface reflections rather than shadows. While the perceptual effect of object elevation with a brightened shadow shape is convincing, it is unnatural. In the present experiment, subjects were undoubtedly aware that the bright patch could not actually be a shadow. This conflict between cognitive and perceptual evidence may have been resolved, to some degree, by imagining the patch to be a surface reflection of the object's underside. Following the experimental testing session, one subject noted that the bright "shadows" appeared similar to reflections. Unlike a shadow, however, the actual distance between an object and its reflection is half of the apparent distance between the object and the reflecting surface. For example, a sphere positioned 1 meter above a mirror will appear 2 meters from the sphere's reflection, since the full distance between the mirror and the sphere will be reflected. Thus, an interpretation of the bright patches as reflections should result in differences in perceived elevation between the two luminance levels. If viewers perceived the negatively luminant shapes as cast shadows and the positively luminant shapes as reflections, then objects with the bright patches should have appeared less elevated than objects with the dark patches underneath, which was not the case.

In addition to the investigation of the shadow luminance in this experiment, results converged with those of Experiment 1. As the separation distance between an object and its shadow was increased, perceptions of object elevation increased accordingly. Furthermore, shadow shape was not a critical factor for the association of a shadow with an object. The elevation ratings obtained in Experiment 4 differed slightly from those obtained in Experiment 1. In general, elevation ratings obtained in Experiment 1 ($M = 52.4$) were somewhat lower than elevation ratings obtained in Experiment 4 ($M = 58.6$). When prior exposure to experimental images is considered, however, there is little

difference in elevation ratings between the experiments. Elevation ratings in Experiment 1 were lowered by the inclusion of subjects who had previously participated in Experiment 2 (discussed in Appendix D, p. 77). Subjects participating in this Experiment 4 had no previous exposure to experimental images. Likewise, half of the subjects in Experiment 1 had no previous exposure to experimental images. Those subjects rated the overall elevation in Experiment 1 ($M = 56.9$) similar to the elevation ratings of subjects participating in Experiment 4 ($M = 58.6$).

A number of complex interactions, presented in Appendix J, demonstrate the ambiguous elevation information conveyed by an object without a shadow. The interactions also suggest that subjects used a variety of cognitive techniques to resolve the ambiguity of the display.

Experiment 5

The first four experiments in this thesis examined the relationship between shadow shape and object shape. These experiments demonstrated that a shadow can be associated with an object, even when there are clearly recognizable differences between the shape of the shadow and the shape of the object. It is possible, however, that the association between a potential shadow and an object is strengthened when there is only one shadow and one object in an image. The purpose of Experiment 5 was to examine the relative importance of object-shadow separation versus shadow shape in the association of a shadow with an object. For example, if a correct shadow shape and an incorrect shadow shape are both placed beneath an object, which shadow is more likely to be assigned to the object? Will assignment be determined by similarity of shape or amount of separation? If shape similarities are more important, viewers should perceive the object as being at the location suggested by the correctly shaped shadow. On the other hand, if a small separation distance between the shadow and object is more important in

the association between shadow and object, viewers should see the object at the position suggested by the nearer, but incorrectly shaped shadow.

The stimulus situation is illustrated in Figures 18, 19, and 20. Images were constructed such that one object, the target object, had two shadows beneath it. An adjacent object, the comparison object, had a single, correct shadow, beneath it. Subjects were asked to judge whether the target object or comparison object appeared nearer. In a control condition, illustrated in Figure 18, the two shadows beneath the target object were both accurate in shape. The control condition examined whether there was a tendency for subjects to assign the shadow with the smaller separation to the target object.

Figure 18. Sample image for Experiment 5. Control condition, with correct shadow shapes in both positions beneath target object.

Figure 19 depicts the target object with the simplified shadow shape in the smaller separation position and the correct shadow shape in the larger separation position. This condition investigated whether a tendency to assign the nearest shadow to the target object would be weakened by a dissimilar shadow shape.

Figure 19. Sample image for Experiment 5. Incorrect shadow shape in smaller separation position.

Finally, Figure 20 shows the target object with the correct shadow shape in the smaller separation position and the simplified shadow shape in the larger separation position. This condition examined whether the association of a shadow with a small separation distance from the target object would be strengthened when an incorrect shadow shape was in the larger separation condition.

Figure 20. Sample image for Experiment 5. Incorrect shadow shape in larger separation position.

In the three experimental conditions, the perception of the relative proximity of the target object and the comparison object depends on which shadow is assigned to the

target object, the nearer shadow, or the more distant shadow. The judgment of the relative proximity of the target and comparison objects reveals which of the two shadows was associated with the target object. The target object would appear more distant than the comparison object if the top shadow (i.e., the shadow with the smaller separation) was assigned to the target object. Alternatively, the target object would appear nearer if the bottom shadow (i.e., the shadow with the larger separation) was assigned to the target object.

Method

Experimental Design. Experiment 5 used four within-subjects independent variables: object shape, simplified shadow position, lateral counterbalancing of objects, and replications. Subjects who participated in Experiment 5 also participated in Experiment 3. As a result, a between subjects independent variable was included: experiment order, to examine possible effects of participating in a prior experiment. The dependent measure in this experiment was a judgment of which object appeared nearer to the viewer (i.e., relative proximity).

Subjects. The 24 subjects who participated in Experiment 3 also served in Experiment 5.

Materials. The computer equipment used in Experiment 5 was the same as used in the earlier experiments of this thesis. Objects and cast shadows used in previous experiments were modified with Adobe Photoshop software. For each image, illustrated in Figures 18 through 20, one of the four objects (complex, cube, torus, or sphere) was placed in the vertical center of the screen and positioned to the left of the horizontal center. A second, identical object appeared to the right of the first object, so that images consisted of object pairs positioned side-by-side. The target object was positioned above two cast shadows. These cast shadows were aligned beneath the object at different vertical separations. The bottom shadow was placed in the position equivalent to the

larger object-shadow separation of Experiment 1 (5.5 cm). The top shadow was positioned just beneath the object, in the smaller object-shadow separation position (2.4 cm). The second object, the comparison object, was always accompanied by a single shadow, positioned at the middle object-shadow separation position of Experiment 1 (3.95 cm). This comparison object was always paired with its correct shadow shape, since this object and shadow served as a reference for judgments about the target object.

The shadows beneath the target object were displayed in one of three possible combinations: (1) correct shadow on top, simplified shadow on bottom; (2) simplified shadow on top, correct shadow on bottom; (3) correct shadow on top and bottom (control condition). The four object shapes were combined with these three shadow configurations. On half of the trials, the target object appeared to the right of the comparison object, while the target object appeared on the left in the remaining trials. For each session, each of these 24 images was presented twice, for a total of 48 trials. As in previous experiments, 12 different stimulus presentation orders were created and used for testing.

Subjects recorded their responses on paper forms with the following question printed at the top "Which of the two objects (if either) appears to be nearer?" Beneath this question, three categorical responses were available for each trial. These three responses allowed subjects to indicate that the left object was nearer, the right object was nearer, or that the two objects appeared at equal proximity.

Procedure. Subjects were seated approximately 60 cm from the computer display and briefed on operation of the computer. Each image was presented for five seconds, followed by a blank screen. At this time, subjects were instructed to indicate which, if either, of the two objects appeared nearer. Once the subject had recorded a response, he or she clicked the mouse button to display the next image. Participants of this experiments also served as subjects in Experiment 3. Consequently, experiment order

was counterbalanced, so that half of the subjects participated in Experiment 5, followed by Experiment 3. This experiment order was reversed for the remaining subjects.

Results

Subjects' evaluations of which of the two objects appeared nearer varied with the position of the simplified cast shadow. Table 1 shows response frequencies, expressed as percentages of all responses, for the relative proximity of the target object collapsed over all four objects. The rows in the table indicate the separation position of the simplified shadow shape, with the first row representing the control condition (with no simplified shadow). The second row indicates judgments with the simplified shadow in the top position (the smaller separation) and the third row represents judgments with the simplified shadow in the bottom position (the larger separation). Columns in Table 1 indicate the frequencies with which the target object was judged to be nearer, further, or the same proximity as the comparison object. A Chi-square test for the distribution of responses represented in Table 1 was significant, $\chi^2(4, N = 1152) = 263.08, p < .001$. In the control condition (i.e., all shadow shapes were correct), the target object was judged to be further away than the comparison object in 50% of the cases. This judgment reveals that the shadow with the smaller separation was associated with the target object in 50% of the judgments, while the shadow with the larger separation was associated with the target object in 24% of the judgments. For the remaining 26% of judgments in the control condition, participants reported that the target object appeared at the same proximity as the comparison object. The second row in Table 1 shows proximity judgments when the simplified shadow appeared in the top position beneath the target object. In this condition, the target object was judged to be nearer 45% of the time. In these instances, subjects associated the correct shadow shape (in the bottom position) with the target object. The last row in Table 1 shows proximity judgments when the simplified shadow appeared in the bottom position. In this condition, the target object was judged to be

more distant 66% of the time. Therefore, subjects most frequently associated the correct shadow shape (in the top shadow position) with the target object.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	24%	26%	50%	384
Simplified Shadow at Top	45%	25%	30%	384
Simplified Shadow at Bottom	14%	20%	66%	384

Table 1. Frequency counts for proximity decisions (all objects included).

Tables 2, 3, 4, and 5 show proximity judgments for each of the four object shapes. Table 2 shows the frequency of responses for the complex object, $\chi^2(4, N = 288) = 205.75, p < .001$. Table 3 shows responses for the cube, $\chi^2(4, N = 288) = 42.19, p < .001$. Table 4 shows responses for the torus, $\chi^2(4, N = 288) = 67.44, p < .001$. Table 5 shows responses for the sphere, $\chi^2(4, N = 288) = 104.44, p < .001$. When the simplified shadow appeared in the bottom position, with the larger separation distance from the target object, the target object was judged to be more distant for all four objects. As Tables 2 through 5 indicate, this testing condition resulted in the majority of responses citing the target object as more distant than the comparison object. For example, the last row of data in Table 2 shows that the target object was judged as more distant in 82% of the presentations. Tables 3, 4, and 5 show responses for the cube (52%), torus (56%) and sphere (74%), respectively. These results indicate that the association of the bottom shadow with the target object was unlikely when the shape of that shadow was incorrect. This is supported by the small number of responses associating the simplified, bottom shadow to the object, ranging from only 7% (for the complex object) to 24% for the torus.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	5%	21%	74%	96
Simplified Shadow at Top	23%	19%	58%	96
Simplified Shadow at Bottom	7%	10%	82%	96

Table 2. Response frequencies on proximity decisions for the complex object.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	17%	43%	41%	96
Simplified Shadow at Top	44%	38%	18%	96
Simplified Shadow at Bottom	16%	32%	52%	96

Table 3. Response frequencies on proximity decisions for the cube object.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	49%	15%	36%	96
Simplified Shadow at Top	58%	22%	20%	96
Simplified Shadow at Bottom	24%	20%	56%	96

Table 4. Response frequencies on proximity decisions for the torus object.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	25%	24%	51%	96
Simplified Shadow at Top	54%	22%	24%	96
Simplified Shadow at Bottom	9%	17%	74%	96

Table 5. Response frequencies on proximity decisions for the sphere object.

In general, the results of the control condition indicate that, when multiple correct shadows are presented beneath an object, there is considerable uncertainty, with a slight tendency to assign the shadow with the smaller separation to the object. This tendency was strong for the complex shape (74%), weak for the sphere (51%), and non-existent for the cube (41%) and the torus (36%).

In the second condition, the top shadow (smaller separation) was replaced with the simplified shadow shape. Under these circumstances, the tendency to assign the nearer shadow was weakened, as the shadow with the smaller separation was assigned to the object in only 30% of the cases, an overall reduction of 20%. For each of the four object shapes, there was a reduction in the tendency to associate the shadow with the object when it was incorrect. The reductions were 16% (decreasing from 74% to 58%) for the complex object, 23% for the cube, 16% for the torus and 27% for the sphere.

In the final condition, the bottom shadow (larger separation) was replaced with the simplified shadow shape. Under these circumstances, results were more consistent, as the tendency to assign the nearer shadow shape was strengthened, as the shadow with the smaller separation was assigned to the object in 66% of the trials. This represented an increase of 16% over the control condition. The increases were 8% (increasing from 74% to 82%) for the complex object, 11% for the cube, 20% for the torus, and 23% for the sphere.

The results of Experiment 5 revealed differences in judgments with different object shapes. Unlike results of Experiments 1 through 3, however, these results did not suggest that responses differed with similarity of object shapes. Proximity decisions were not consistent for the two angular objects or for the two rounded objects. The variance in responses for the different object shapes suggest that subjects' decisions may have been influenced by a response bias.

Lateral position of the target object appeared to have little effect on proximity judgments. Tables for lateral positioning are presented in Appendix K.

Summary and Discussion

The results of Experiment 5 suggest that both shape correspondence and object-shadow separation are important factors for associating an object with a shadow. In general, the results of this experiment indicated that, when conflicting cast shadows of the same shape are available, the nearer shadow will be associated with the object. This was

demonstrated by the control condition, where the nearer of two correct shadow shapes dictated the relative proximity of the two objects. This effect was mediated, however, by shadow shape.

The results suggest that shadow shape may be a more important determinant in associating a shadow with an object than decreased separation distance between a shadow and object. This conclusion is supported by the judgments of images containing the simplified shadow in the top shadow position. Although the simplified shadow appeared in the position between the target object and its correct shadow shape, subjects most often perceived the object as being located in the position suggested by the correct, but more separated, shadow shape. This reveals that the corresponding shadow shape was associated with the object, while the nearer simplified shadow was overlooked. An alternate interpretation is that the simplified shadow was ineffective as a shadow.

The results of Experiment 1 suggested that a cast shadow of any shape was effective in affecting the apparent location of an object. Additionally, the combined results of Experiments 1 and 2 suggested that the simplified shadow shape was an acceptable alternative to the correct shadow shapes for the objects studied. Results of Experiment 5, however, indicated that the simplified shadow shape was less acceptable when a correct shadow shape was present. This suggests that, although shadow shape is not a critical feature for shadow assignment, shadow shape is a factor in the association of a shadow with an object, particularly in the presence of corresponding shadow shapes.

Ratings of the two objects being the same proximity from the viewer were relatively high. If subjects did use the shadow information, regardless of which shadow was associated with the target object, the objects could not appear at the same proximity. If the top shadow was associated with the target object, it would appear more distant than the comparison object. Similarly, if the bottom shadow was associated with the target object, it would appear more proximal than the comparison object. The frequency of responses that the objects were equally proximal suggests one of three interpretations.

First, responses of this kind may indicate that subjects had difficulty making proximity decisions. Thus, subjects used the "same" response to indicate an inability to decide. Second, a "same" response would be valid if no shadows were displayed beneath the objects. This suggests that subjects may have ignored all shadows beneath the two objects. Third, if attention switched between the two shadows, they would alternately appear nearer and further away than the comparison. Under these circumstances, some subjects might have used the category "same" as the most reasonable of a set of three inappropriate categories.

The large amount of variance and high number of "same" judgments may point to the difficulty of making spatial judgments in the presence of conflicting spatial cues. Although the present experiment did not examine the issue, it is reasonable to speculate that visual attention played an important role in proximity decisions. When a viewer's visual attention is focused on the more separated of two conflicting, correctly shaped shadows, the object appears more proximal and more elevated than when the less separated shadow is associated with the object. Alternatively, when the viewer's visual attention is focused on the less separated shadow, the object appears less proximal and less elevated than when the more separated shadow is associated with the object. Consequently, visual attention to a shadow can be attenuated by manipulations to its shape and its distance from the casting object. When multiple, conflicting shadows are available, increasing the shape correspondence and decreasing its separation increase the likelihood that the shadow will be attended to and, in turn, will be associated to the casting object.

For all test images, it was possible to interpret either of the two objects as nearer, depending on whether the viewer attended to the less separated or more separated shadow shape. Moreover, the high frequency of judgments that the objects were equally proximal also suggests that it was possible for all shadows to be ignored. For example, a subject who could not readily resolve the visual conflict presented by multiple cast

shadows may have simply ignored all of the shadows. Alternatively, in the presence of correct cast shadows, subjects may not have seen the simplified shadow shape as a shadow. For example, it may have been interpreted as a hole in the ground plane. In either case, the two objects would appear to be equally proximal. Consequently, the results obtained in this experiment may provide more information about how visual ambiguity is resolved than how a cast shadow is associated with an object.

General Discussion

Importance of Shadow Shape

The five experiments in this thesis addressed the importance of similarity of object and shadow shape in associating a shadow with an object. Results of these experiments suggest that, although shape does play a role when conflicting shadow shapes are present, a high degree of shape correspondence is not necessary in order for a cast shadow to serve effectively as a depth cue. Although this issue has not been examined empirically before, the results are consistent with prior hypotheses that the human visual system is tolerant of shape deviations in shadows (e.g., Yonas, 1979; Cavanagh & Leclerc, 1989; Herndon et al., 1992).

The present research suggests that, in the presence of cast shadows, depth perception is enhanced when the shape of the shadow resembles the shape of the casting object. For example, the present research suggests that the perceived change in object elevation is greatest when an angular shadow appears beneath an angular object or when a rounded shadow appears beneath a rounded object. Shape similarity between shadow and object also appears to be a reason that, relative to other incorrect shadow shapes used in the present research, the simplified shadow was the most accepted universal shadow for all four object shapes. Of the five shadow shapes in the experimental set, the simplified cast shadow contains both angular and rounded features, while the four remaining

shadows contain only angular (complex and cube shadows) or only rounded features (torus and sphere shadows).

Cognition vs Perception

On the basis of the present research, it is not possible to determine the extent to which the association of an incorrect shadow shape with an object is a visual process, a cognitive process, or both. Experiment 2 demonstrated that, without question, subjects know that an incorrect shadow shape is incorrect. Yet subjects repeatedly used these incorrect shadow shapes to accurately judge the position of objects. It is possible that, in the context of an experiment making judgments with correct shadows, subjects made the decision to treat incorrect shadows as if they were correct. Alternatively, it is possible that the visual system automatically processed the incorrect shadow shapes as appropriate cast shadows.

In Experiments 1, 4, and 5, images were displayed for five seconds. This interval was established through pilot testing of various display times. A display of this length allowed subjects to examine the objects in the image thoroughly, but also increased the possibility that judgments were cognitively mediated. As a result, this series of studies does not provide evidence that use of an incorrect shadow shape for making location judgments is solely a visual process.

Visual Attention

Visual attention appears to play an important role in the association of a cast shadow to an object. In Experiments 1, 2, 3 and 4, a single object appeared above a single shadow. Consequently, visual attention did not play a role in shadow association. Attending to either the object or the shadow, in this situation, resulted in the same perception of object elevation. When two shadows were presented beneath an object, however, proximity judgments were determined by which potential shadow the subject attends to. For example, it was possible to differentially attend to selected components in the complex images presented in Experiment 5. If the subject attended primarily to the

target and the shadow with smaller separation, the target appeared further away. If the subject attended primarily to the target and the shadow with larger separation, the target appeared closer to the subject. If the subject attended primarily to both objects, ignoring the shadows, the two objects appeared equidistant. What cannot be answered by the current experiments is whether the subjects chose to direct their attention to correct shapes (a cognitive process), whether similar shapes drew the visual attention to them (a visual process), or whether incorrect shapes directed attention (cognitively or visually) to the correct shapes. It is even possible that some subjects on some trials did not even consider the simplified shape as a shadow when a correct shadow was present. When a correct shadow shape was present, the simplified shadow may have been treated as an irrelevant object in the display. When both a correct and incorrect shadow shape appeared beneath an object, the correct shadow shape was generally perceived as a shadow, but how this occurred is not clear.

Separation Distance between Object and Shadow

In addition to shape similarities between object and shadow, the present research suggests that a secondary factor in associating a cast shadow with an object is the separation distance between the object and its shadow. As the separation distance between an object and a shadow is reduced, the association of the shadow to that object appears to be strengthened. The results of Experiment 5 suggest, however, that separation distance is less important for shadow association than shape similarity between the object and shadow.

Shadow Luminance

The role of shadow luminance was also examined. Experiment 4 revealed that negative luminance is not a critical component of a cast shadow. Shadows that were brighter than the shadowed surface affected perceptions of object location, in a manner similar to dark shadows. These results do not support Cavanagh and Leclerc (1989), who hypothesized that a shadow shape must be darker than its surround to be perceived as a

cast shadow of an object. In practice, however, bright cast shadows would have limitations. The visual effect of a bright cast shadow beneath an object is convincing, but unnatural. Although the bright shadow shapes altered ratings of object elevation in experimental testing, it is possible that they were not processed as cast shadows. The bright shadow shapes may have been interpreted as object reflections on the ground plane. On the other hand, the stippled appearance of the ground suggested a finely textured surface, which should not have appeared reflective to the subjects. Furthermore, if the bright shapes were interpreted as reflections while the dark shapes were interpreted as shadows, elevation ratings should have differed by luminance levels, which was not the case. Consequently, future research is recommended to further examine whether luminant shapes beneath objects may be processed as shadows, reflections, or whether the present results were an artifact of the experimental design employed.

Implications for Computer Graphics

Effectiveness of shadows as a depth cue

Results of the present research is consistent with earlier studies, which suggested that cast shadows are essential in determining the spatial location of objects (Yonas, Goldsmith, & Hallstrom, 1979; Wanger, Ferwerda, & Greenberg, 1992; Wanger, 1992). When cast shadows are absent, the location of an object is ambiguous in a pictorial display. This conclusion is supported by the group differences in the perception of objects without shadows in Experiment 1. Subjects who had already participated in Experiment 2, and thus were accustomed to seeing objects with shadows, frequently perceived shadowless objects as floating above the ground surface. Conversely, subjects who had not been exposed to the images in Experiment 2 tended to perceive the shadowless objects as resting on the ground surface. This converges with previous research which showed that, in the absence of cast shadows, the position of an object

above a ground plane is ambiguous and, thus, viewers cannot determine the location of objects better than chance (Wanger, 1992).

Images generated in computer graphics applications can be divided into three different categories: static images, animated images, and interactive images. Images containing correct cast shadow shapes are computationally demanding to generate. Once the image is generated, however, the computational costs of displaying an image with correct shadows or an image with simplified shadows are identical. For this reason, the computational demands of displaying shadows in static and non-interactive animated images are of little consequence. Because interactive, real-time graphics applications require that images be generated as they are displayed, however, the computational demands of correct shadows can interfere with system performance. For this reason, interactive, real-time graphics applications would benefit most from the inclusion of simplified cast shadows.

Although simplified cast shadows are not beneficial for all graphics software applications, they are particularly important for tasks in computer-aided design (CAD) software. The implementation of simplified cast shadows in CAD applications would provide information about the spatial location of objects. At present, determining the spatial location of the objects in CAD software requires multiple views of the scene (for example, a front view and a side view) to determine object proximity and elevation. The inclusion of cast shadows could reduce the need for multiple views on a scene, since a simplified cast shadow can accurately provide this information.

Other computer applications that may benefit from implementing simplified cast shadows are simulations. Simulation software includes architectural walkthroughs, flight simulations, and virtual reality applications. In the present research, the ground plane, and thus, the shadowed surface, was always flat. This is generally appropriate for computer-aided design applications. The irregular ground surfaces found in simulation software, however, would present challenges for the inclusion of simplified shadow

shapes. When a shadow appears on an irregular surface, some shape transformation would be expected by the viewer. Consequently, future research is necessary in order to examine the effectiveness of stable shadow shapes on irregular surfaces.

The incorporation of simplified shadows should be under control of the user. Users should be able to display objects with no shadows, simplified shadows, or accurate shadows. For example, a designer using CAD software might elect to work without shadows when working with a single object. In this case, the designer does not need information about the relative location of objects. As the designer's scene becomes more complex, the addition of simplified cast shadows can provide information about the relative positions of the objects on screen. If the designer needs additional information to resolve the shape of an ambiguous object, accurate cast shadows can be applied to the scene. Once the shape ambiguity is resolved, the designer can display the image without shadows or with simplified shadows to improve system response time.

In interactive, real-time displays, the objects in the computer scene will move. The present research did not examine moving objects. When an object and shadow move across the display, it is reasonable to speculate that the association between the object and shadow will be strengthened. Thus, a simplified cast shadow should be even more compelling when applied to real-time graphics displays.

Simplifying shadow shape

In all experiments for this thesis, the simplified shadow shape shared features with the objects in the experimental set. In this case, the simplified shadow was the only shadow shape that contained both angular and rounded features. Consequently, the simplified shadow was selected as the best universal shadow for the four objects investigated. Moreover, in the present research, all objects were roughly the same size. Because objects appeared to share similar width, depth, and height, it was not difficult to find a single simplified shadow that was acceptable. Deriving a simplified cast shadow for a larger set of objects may be more difficult. This is particularly true if the objects

vary greatly in size. A possible solution to this problem is to scale the shadow to reflect the appropriate width and depth of the casting object. Although this would increase the computational demands slightly, it would still be more efficient than generating an accurate shadow shape.

Confusability of object shape from simplified shadows

The results of the present thesis suggest future research, of both theoretical and practical importance, on cast shadows. In interactive computer applications, objects may not always be displayed in their most descriptive view. Objects may appear in foreshortened views, revealing little information about the shape of the object. Objects displayed in a foreshortened view may not be readily identifiable without precise cast shadow shapes. It is possible that a simplified cast shadow might have a negative effect on object recognition, causing the viewer to infer an inaccurate shape for the object. Even if the viewer does not misinterpret the object shape on the basis of a simplified cast shadow, the time necessary to recognize the shape of the object may increase. Research on object recognition in the presence of simplified cast shadows can examine these potential problems.

Results of the research on shadow luminance suggested that bright shadow shapes altered perception of object elevation similar to dark shadow shapes. It is possible that this effect occurs by interpreting the positively luminant shape as a surface reflection, rather than a cast shadow. Additional research on this topic can provide answers to whether a positively luminant shape beneath an object functions as a cast shadow or as a surface reflection of the object's underside.

Shadow movement

In the present research, experiment trials consisted of static images. In a real-time system, objects on screen may move due to the motion of the object, or due to the motion of the user. In either case, the paired motion of the object and its cast shadow would reinforce the viewer's association of the shadow with that object. When an object is

relocated from one position to another, the simplified cast shadow can simply be relocated to its appropriate location. In this case, no additional computations are necessary to display the simplified shadow. Movements involving object orientation are more problematic.

For example, when an object remains in its location and is rotated around the object's center, one of two approaches can be taken with the simplified shadow. The simplified shadow shape can either change shape to indicate changes in the object's orientation or its shape can remain stable. The two approaches present different problems. If the shape of the shadow is altered to reflect the rotation of the object, the computational demands of the simplified shadow are increased and its advantage over a correct shadow shape is lost. Alternatively, if the simplified shadow is implemented so that it retains its original shape, the apparent relationship to the object will be lost, since the object will appear to move while its shadow remains still. Before simplified shadows are included with rotating objects, it will be necessary to determine how to handle this problem.

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Appendix A

Sample image for Experiment 1. Sphere object at separation distance of 3.95 cm, with and without shadow.

Appendix B

All object shapes and shadow shapes for
Experiment 1

Complex Object

Cube

Sphere

Torus

Simplified Shadow

Torus Shadow

Sphere Shadow

Complex Shadow

Cube Shadow

Appendix C

Sample rating form for Experiment 1

Does the object with the shadow appear more, equal or less elevated than the object without the shadow?

	1	2	3	4	5	6	7	8	9	10	
+	+										
more elevated											
equal											
less elevated											
+	+										+
	11	12	13	14	15	16	17	18	19	20	
+	+										
more elevated											
equal											
less elevated											

Appendix D

Extraneous results for Experiment 1

The order in which subjects participated in Experiments 1 and 2 influenced subjects' judgments of object elevation. This is noted by the significant main effect of experiment order, univariate $F(1, 22) = 5.01, p < .04$. In general, subjects who had not yet participated in Experiment 1 tended to perceive objects as increasing in elevation when cast shadows were added ($M = 56.9$). In contrast, subjects who had already participated in Experiment 2 tended to perceive objects as decreasing slightly in elevation when cast shadows were added ($M = 48.0$).

The interaction of object shape with replications was statistically significant, univariate $F(3, 69) = 3.54, p < .02$, as revealed by the univariate test of significance. Figure D-1 shows the change in perceived elevation on the vertical axis with separate categories for object shape on the horizontal axis. Each replication is shown on a separate bar. For example, the leftmost pair of bars shows the mean elevation change for the first and second replications when the complex object shape was used. This graph reveals that perceived elevation change for angular objects (complex and cube) decreased with the second replication. Conversely, perceived elevation change for rounded objects (torus and sphere) was higher for the second replication. In all cases the changes were small. The largest change from the first to second replication was a reduction of 1.9 for the cube. The interaction between replication and object shape in Figure D-1 did not vary with shadow shape, multivariate $F(12, 11) = 2.26, p > .09$, with object-shadow separation, univariate $F(6, 132) = 1.48, p > .15$, or with the combination of shadow shape and separation, univariate $F < 1$.

Figure D-1. Interaction between object shape and replication order.

Discussion

Subjects who participated in Experiment 1 prior to Experiment 2 perceived objects as increasing in elevation when a shadow was added, while subjects who had participated in Experiment 2 prior to Experiment 1 perceived objects as decreasing slightly in elevation when a cast shadow was added to the image. This difference in ratings for the two experiment orders appears to be the result of prior exposure of half of the subjects to experimental images. More specifically, the first image for each trial in Experiment 1 contained no cast shadow. As a result, perception of the object's baseline elevation was ambiguous. Subjects could perceive the object without a shadow as either resting on, or floating above, the ground surface.

The following interpretation seems plausible. Objects shown in Experiment 2 always appeared with shadows. Consequently, subjects who had already participated in Experiment 2 were familiar with images of objects with shadows. The absence of cast shadows in Experiment 1, however, often caused those subjects to interpret objects without shadows as floating above the surface of the ground. Subjects who had

participated in Experiment 2 interpreted rounded objects (i.e., the torus and sphere) without shadows as objects floating above the ground plane, with cast shadows falling outside of the image region. For these subjects, the addition of a cast shadow to an object resulted in the appearance of the object actually decreasing in elevation. When shadows were absent, these subjects did not necessarily perceive angular objects as floating, since a cube or complex object resting on the ground could conceal a cast shadow beneath the base of the object. The sphere and torus are difficult to perceive as resting on the ground surface, however, since a cast shadow would be revealed beneath the object. In contrast to subjects that participated in Experiment 2 first, subjects who had not been exposed to the images in Experiment 2 had no difficulty in simply perceiving either angular or rounded objects as resting on the ground surface in baseline images. As a result, subjects with no prior exposure to images with shadows perceived objects as becoming more elevated when a shadow was added beneath an object.

Appendix E

MANOVA tables for all experiments

Table E-1: Experiment 1 MANOVA Table. Univariate Fs reported unless otherwise indicated (*).

Asterisks indicate multivariate Fs.

<u>Effect</u>	<u>F</u>	<u>df</u>	<u>p</u>
Experiment Order	5.01	1, 22	.036
Replication	.04	1, 22	.836
Exp. Order x Replication	2.25	1, 22	.148
Object*	3.91	3, 20	.024
Exp. Order x Object*	1.08	3, 20	.380
Shadow*	1.04	4, 19	.410
Exp. Order x Shadow*	2.00	4, 19	.135
Separation*	7.29	2, 21	.004
Exp. Order x Separation*	.12	2, 21	.884
Replication x Object	3.53	3, 66	.019
Exp. Order x Replication x Object	.91	3, 66	.441
Replication x Shadow	1.16	4, 88	.334
Exp. Order x Replication x Shadow	.31	4, 88	.871
Replication x Separation*	2.74	2, 21	.088
Exp. Order x Replication x Separation*	2.96	2, 21	.074
Object x Shadow*	3.48	12, 11	.024
Exp. Order x Object x Shadow*	1.48	12, 11	.261
Object x Separation*	1.17	6, 17	.365
Exp. Order x Object x Separation*	1.32	6, 17	.300
Shadow x Separation*	1.83	8, 15	.149
Exp. Order x Shadow x Separation*	1.94	8, 15	.128
Replication x Object x Shadow*	2.26	12, 11	.094
Exp. Order x Replication x Object x Shadow*	1.98	12, 11	.134
Replication x Object x Separation	1.48	6, 132	.191
Exp. Order x Replication x Object x Separation	1.57	6, 132	.160
Replication x Shadow x Separation	2.26	8, 15	.083
Exp. Order x Replication x Shadow x Separation	.45	8, 15	.869
Object x Shadow x Separation	.64	24, 528	.909
Exp. Order x Object x Shadow x Separation	1.03	24, 528	.427
Replication x Object x Shadow x Separation	.97	24, 528	.510
Exp. Order x Replication x Object x Shadow x Separation	.49	24, 528	.981

Table E-2: Experiment 2 MANOVA Table. Asterisks indicate multivariate Fs.

Effect	E	df	p
Experiment Order	2.79	1, 22	.109
Shadow	48.22	1, 22	.000
Exp. Order x Shadow	.71	1, 22	.408
Replication	.38	1, 22	.544
Exp. Order x Replication	1.95	1, 22	.176
Object*	11.89	3, 20	.000
Exp. Order x Object*	.39	3, 20	.755
Shadow x Replication	.04	1, 22	.835
Exp. Order x Shadow x Replication	1.87	1, 22	.185
Shadow x Object*	1.16	3, 20	.351
Exp. Order x Shadow x Object*	.09	3, 20	.964
Replication x Object	1.60	3, 66	.198
Exp. Order x Replication x Object	.29	3, 66	.836
Shadow x Replication x Object	.58	3, 66	.633
Exp. Order x Shadow x Replication x Object	.09	3, 66	.965

Table E-3: Experiment 3 MANOVA Table. Positions ordered by Elevation. Asterisks indicate multivariate Fs.

Effect	E	df	p
Experiment Order	.03	1, 22	.874
Shadow	.29	1, 22	.598
Exp. Order x Shadow	.22	1, 22	.641
Replication	3.67	1, 22	.068
Exp. Order x Replication	.44	1, 22	.516
Object	2.04	3, 66	.116
Exp. Order x Object	1.05	3, 66	.376
Position	8.99	5, 110	.000
Exp. Order x Position	.48	5, 110	.790
Shadow x Replication	.61	1, 22	.442
Exp. Order x Shadow x Replication	.61	1, 22	.444
Shadow x Object	2.45	3, 66	.071
Exp. Order x Shadow x Object	.08	3, 66	.969
Shadow x Position	2.11	5, 110	.070
Exp. Order x Shadow x Position	.47	5, 110	.796
Replication x Object	.05	3, 66	.983
Exp. Order x Replication x Object	1.60	3, 66	.199
Replication x Position	3.75	5, 110	.004
Exp. Order x Replication x Position	1.28	5, 110	.278
Object x Position*	26.59	15, 8	.000
Exp. Order x Object x Position*	1.76	15, 8	.211
Shadow x Replication x Object	.91	3, 66	.442
Exp. Order x Shadow x Replication x Object	.47	3, 66	.705
Shadow x Replication x Position	.20	5, 110	.961
Exp. Order x Shadow x Replication x Position	.35	5, 110	.882
Shadow x Object x Position	1.83	15, 330	.030
Exp. Order x Shadow x Object x Position	1.69	15, 330	.051
Replication x Object x Position*	4.43	15, 8	.020
Exp. Order x Replication x Object x Position*	1.59	15, 8	.257
Shadow x Replication x Object x Position*	1.06	15, 8	.488
Exp. Order x Shadow x Replication x Object x Position*	1.03	15, 8	.509

Table E-4: Experiment 3 MANOVA Table. Positions ordered by Proximity. Asterisks indicate multivariate Fs.

<u>Effect</u>	<u>F</u>	<u>df</u>	<u>p</u>
Experiment Order	.03	1, 22	.874
Shadow	.29	1, 22	.598
Exp. Order x Shadow	.22	1, 22	.641
Replication	3.67	1, 22	.068
Exp. Order x Replication	.44	1, 22	.516
Object	2.04	3, 66	.116
Exp. Order x Object	1.05	3, 66	.376
Position*	12.13	5, 18	.000
Exp. Order x Position*	1.31	5, 18	.303
Shadow x Replication	.61	1, 22	.442
Exp. Order x Shadow x Replication	.61	1, 22	.444
Shadow x Object	2.45	3, 66	.071
Exp. Order x Shadow x Object	.08	3, 66	.969
Shadow x Position*	6.14	5, 18	.002
Exp. Order x Shadow x Position*	3.18	5, 18	.031
Replication x Object	.05	3, 66	.983
Exp. Order x Replication x Object	1.60	3, 66	.199
Replication x Position*	6.91	5, 18	.001
Exp. Order x Replication x Position*	2.14	5, 18	.107
Object x Position*	12.69	15, 8	.001
Exp. Order x Object x Position*	3.26	15, 8	.048
Shadow x Replication x Object	.91	3, 66	.442
Exp. Order x Shadow x Replication x Object	.47	3, 66	.705
Shadow x Replication x Position	.57	5, 110	.719
Exp. Order x Shadow x Replication x Position	.72	5, 110	.608
Shadow x Object x Position*	1.56	15, 8	.267
Exp. Order x Shadow x Object x Position*	1.81	15, 8	.200
Replication x Object x Position	2.38	15, 330	.003
Exp. Order x Replication x Object x Position	1.44	15, 330	.128
Shadow x Replication x Object x Position*	.75	15, 8	.696
Exp. Order x Shadow x Replication x Object x Position*	1.48	15, 8	.292

Table E-5: Experiment 4 MANOVA Table. Asterisks indicate multivariate Fs.

Effect	E	df	p
Experiment Order	1.43	1, 22	.245
Replication	6.26	1, 22	.020
Exp. Order x Replication	1.74	1, 22	.201
Object	17.68	1, 22	.000
Exp. Order x Object	15.16	1, 22	.001
Shadow	.70	2, 44	.504
Exp. Order x Shadow	.86	2, 44	.431
Separation	71.20	2, 44	.000
Exp. Order x Separation	33.83	2, 44	.000
Luminance	.46	1, 22	.503
Exp. Order x Luminance	5.79	1, 22	.025
Replication x Object	1.13	1, 22	.299
Exp. Order x Replication x Object	.01	1, 22	.911
Replication x Shadow*	.47	2, 21	.629
Exp. Order x Replication x Shadow*	.86	2, 21	.439
Replication x Separation	.99	2, 44	.380
Exp. Order x Replication x Separation	.11	2, 44	.897
Replication x Luminance	2.01	1, 22	.171
Exp. Order x Replication x Luminance	.14	1, 22	.708
Object x Shadow*	.35	2, 21	.708
Exp. Order x Object x Shadow*	.07	2, 21	.930
Object x Separation	4.78	2, 44	.013
Exp. Order x Object x Separation	.43	2, 44	.651
Object x Luminance	5.81	1, 22	.025
Exp. Order x Object x Luminance	1.32	1, 22	.263
Shadow x Separation	2.14	4, 88	.083
Exp. Order x Shadow x Separation	2.76	4, 88	.032
Shadow x Luminance	2.53	2, 44	.092
Exp. Order x Shadow x Luminance	1.66	2, 44	.202
Separation x Luminance	1.04	2, 44	.362
Exp. Order x Separation x Luminance	4.29	2, 44	.020
Replication x Object x Shadow	.19	2, 44	.825
Exp. Order x Replication x Object x Shadow	1.34	2, 44	.272
Replication x Object x Separation	2.15	2, 44	.128

Exp. Order x Replication x Object x Separation	3.73	2, 44	.032
Replication x Object x Luminance	1.05	1, 22	.317
Exp. Order x Replication x Object x Luminance	.03	1, 22	.864
Replication x Shadow x Separation	.57	4, 88	.688
Exp. Order x Replication x Shadow x Separation	1.21	4, 88	.311
Replication x Shadow x Luminance*	1.18	2, 21	.325
Exp. Order x Replication x Shadow x Luminance*	2.54	2, 21	.103
Replication x Separation x Luminance*	.15	2, 21	.865
Exp. Order x Replication x Separation x Luminance*	.29	2, 21	.749
Object x Shadow x Separation*	3.67	4, 19	.022
Exp. Order x Object x Shadow x Separation*	2.86	4, 19	.052
Object x Shadow x Luminance	4.46	2, 44	.017
Exp. Order x Object x Shadow x Luminance	2.19	2, 44	.125
Object x Separation x Luminance	3.01	2, 44	.059
Exp. Order x Object x Separation x Luminance	.81	2, 44	.450
Shadow x Separation x Luminance	3.01	4, 88	.022
Exp. Order x Shadow x Separation x Luminance	2.96	4, 88	.024
Replication x Object x Shadow x Separation	.72	4, 88	.579
Exp. Order x Replication x Object x Shadow x Separation	1.76	4, 88	.144
Replication x Object x Shadow x Luminance	1.96	2, 44	.153
Exp. Order x Replication x Object x Shadow x Luminance	.27	2, 44	.764
Replication x Object x Separation x Luminance	.43	2, 44	.655
Exp. Order x Replication x Object x Separation x Luminance	.85	2, 44	.433
Replication x Shadow x Separation x Luminance*	.06	4, 19	.992
Exp. Order x Replication x Shadow x Separation x Luminance*	.30	4, 19	.872
Object x Shadow x Separation x Luminance*	1.73	4, 19	.186
Exp. Order x Object x Shadow x Separation x Luminance*	2.79	4, 19	.056
Replication x Object x Shadow x Separation x Luminance*	.96	4, 19	.450
Exp. Order x Replication x Object x Shadow x Separation x Luminance*	1.24	4, 19	.327

Appendix F

Sample image from Experiment 3. Sphere object located at elevation position of 5 and proximity position of 5.

Appendix G

Additional MANOVA tables for Experiment 3. Proximity and elevation errors treated independently.

Table G-1: Experiment 3 MANOVA Table. Positions ordered by proximity, with proximity and elevation treated independently. Multivariate Fs reported unless otherwise indicated (*). Asterisks indicate averaged Fs.

<u>Effect</u>	<u>F</u>	<u>df</u>	<u>p</u>
Experiment Order	1.13	2, 21	.340
Shadow	4.96	2, 21	.017
Exp. Order x Shadow	2.04	2, 21	.155
Replication	2.04	2, 21	.155
Exp. Order x Replication	.93	2, 21	.411
Object	21.40	6, 17	.000
Exp. Order x Object	.48	6, 17	.814
Position	24.62	10, 13	.000
Exp. Order x Position	.82	10, 13	.617
Shadow x Replication	.98	2, 21	.393
Exp. Order x Shadow x Replication	1.54	2, 21	.237
Shadow x Object	2.80	6, 17	.044
Exp. Order x Shadow x Object	.89	6, 17	.520
Shadow x Position	1.70	10, 13	.182
Exp. Order x Shadow x Position	.80	10, 13	.633
Replication x Object	.05	3, 66	.983
Exp. Order x Replication x Object	.14	6, 17	.989
Replication x Position	1.82	6, 17	.362
Exp. Order x Replication x Position	1.44	10, 13	.264
Object x Position*	10.61	30, 658	.000
Exp. Order x Object x Position*	.99	30, 658	.483
Shadow x Replication x Object	3.69	6, 17	.016
Exp. Order x Shadow x Replication x Object	1.40	6, 17	.272
Shadow x Replication x Position	.36	10, 13	.078
Exp. Order x Shadow x Replication x Position	.95	10, 13	.522
Shadow x Object x Position*	3.40	30, 658	.000
Exp. Order x Shadow x Object x Position*	1.60	30, 658	.023
Replication x Object x Position*	6.29	30, 658	.000
Exp. Order x Replication x Object x Position*	.75	30, 658	.833
Shadow x Replication x Object x Position*	1.85	30, 658	.004
Exp. Order x Shadow x Replication x Object x Position*	.92	30, 658	.584

Table G-2: Experiment 3 MANOVA Table. Positions ordered by elevation, with proximity and elevation treated independently. Multivariate Fs reported unless otherwise indicated (*). Asterisks indicate averaged Fs.

<u>Effect</u>	<u>F</u>	<u>df</u>	<u>p</u>
Experiment Order	1.13	2, 21	.340
Shadow	4.96	2, 21	.017
Exp. Order x Shadow	2.04	2, 21	.155
Replication	2.04	2, 21	.155
Exp. Order x Replication	.93	2, 21	.411
Object	12.15	6, 17	.000
Exp. Order x Object	.67	6, 17	.673
Position	22.06	10, 13	.000
Exp. Order x Position	1.17	10, 13	.388
Shadow x Replication	.98	2, 21	.393
Exp. Order x Shadow x Replication	1.54	2, 21	.237
Shadow x Object	2.80	6, 17	.044
Exp. Order x Shadow x Object	1.18	6, 17	.361
Shadow x Position	3.06	10, 13	.031
Exp. Order x Shadow x Position	4.08	10, 13	.010
Replication x Object	29.28	6, 17	.000
Exp. Order x Replication x Object	1.22	6, 17	.343
Replication x Position	21.64	10, 13	.000
Exp. Order x Replication x Position	.57	10, 13	.809
Object x Position*	10.56	30, 658	.000
Exp. Order x Object x Position*	1.03	30, 658	.424
Shadow x Replication x Object	1.15	6, 17	.376
Exp. Order x Shadow x Replication x Object	1.64	6, 17	.197
Shadow x Replication x Position	1.14	10, 13	.402
Exp. Order x Shadow x Replication x Position	.65	10, 13	.751
Shadow x Object x Position*	3.20	30, 658	.000
Exp. Order x Shadow x Object x Position*	1.06	30, 658	.380
Replication x Object x Position*	16.08	30, 658	.000
Exp. Order x Replication x Object x Position*	.87	30, 658	.665
Shadow x Replication x Object x Position*	2.65	30, 658	.000
Exp. Order x Shadow x Replication x Object x Position*	1.13	30, 658	.291

Appendix H

Extraneous results for Experiment 3

When position was ordered by elevation, position interacted with replications (Figure H-1), univariate $F(5, 110) = 3.75, p < .01$, with objects (Figure H-2), multivariate $F(15, 8) = 26.596, p < .001$, and with shadows and objects (Figures H-3 - H-6), univariate $F(15, 330) = 1.83, p < .04$.

Figure H-1. Interaction of elevation position with replication.

Figure H-2. Interaction of elevation position with objects.

Figure H-3. Interaction of elevation position, shadows, and objects for the complex object.

Figure H-4. Interaction of elevation position, shadows, and objects for the cube object.

Figure H-5. Interaction of elevation position, shadows, and objects for the torus object.

Figure H-6. Interaction of elevation position, shadows, and objects for the sphere object.

When position was ordered by proximity, position interacted with shadows (Figure H-7), multivariate $F(5, 18) = 6.136$, $p < .01$, with replications (Figure H-8), multivariate $F(5, 18) = 6.91$, $p < .005$, and with objects (Figure H-9), multivariate $F(15, 8) = 12.69$, $p < .005$.

Figure H-7. Interaction of proximity position with shadow shape.

Figure H-8. Interaction of proximity position with replications.

Figure H-9. Interaction of proximity position with objects.

When position was ordered by proximity, higher order interactions with position included replications and objects (Figures H-10 - H-13), multivariate $F(15, 330) = 2.38$, $p < .003$, shadows and experiment order (Figures H-14 - H-15), multivariate $F(5, 18) = 3.182$, $p < .05$, and objects and experiment order (Figures H-16 - H-19), multivariate $F(15, 8) = 3.263$, $p < .05$. None of these interactions with position varied systematically with the other independent variables.

Figure H-10. Interaction of proximity position with replications and objects, for the complex object.

Figure H-11. Interaction of proximity position with replications and objects, for the cube object.

Figure H-12. Interaction of proximity position with replications and objects, for the torus object.

Figure H-13. Interaction of proximity position with replications and objects, for the sphere object.

Figure H-14. Interaction of position with experiment order and shadows, for correct shadow shape.

Figure H-15. Interaction of position with experiment order and shadows, for simple shadow shape.

Figure H-16. Interaction of proximity position with experiment order and object, for complex object.

Figure H-17. Interaction of proximity position with experiment order and object, for cube object.

Figure H-18. Interaction of proximity position with experiment order and object, for torus object.

Figure H-19. Interaction of proximity position with experiment order and object, for sphere object.

Appendix I

Sample images from Experiment 4: Negative and
positive luminance for shadows

Appendix J

Extraneous results for Experiment 4

The three-way interaction between separation, shadow shape and object shape was significant, multivariate $F(4, 19) = 3.67, p < .03$. Figure J-1 shows the mean elevation change for the interaction between object-shadow separation and shadow shape for the complex object. Elevation change is shown on the vertical axis, with object-shadow separation distance shown on the horizontal axis. Each bar represents one of the three shadow shapes. Figure J-2 shows the interaction between object-shadow separation and shadow shape for the sphere. These graphs show that, for both objects, the effect of object-shadow separations was as expected. The figures also show that the size of differences varied non-systematically for the complex object and sphere object. For example, as Figure J-1 indicates, when the complex shadow shape was paired with the complex object (represented by the solid black bars), ratings were the lowest of all object and shadow pairings for the small separation. Conversely, the pairing of the complex shadow shape and complex object was rated the highest of all pairings for medium and large separations. A similar pattern was obtained for the sphere object in Figure J-2. Elevation change was lowest when the sphere shadow was paired with the sphere object (represented by the darker gray bars) for the small separation. Conversely, Figure J-2 shows that elevation ratings were increased when the sphere object and sphere shadow were paired in the medium and largest separation conditions. The three-way interaction, though statistically significant, does not appear to be interpretable.

Figure J-1. Interaction between object shape, shadow shape, and separation for the complex object.

Figure J-2. Interaction between object shape, shadow shape, and separation for the sphere.

The three-way interaction between shadow shape, object-shadow separation and luminance was significant, univariate $F(4, 88) = 3.01, p < .03$. Figures J-3 through J-5

show the three-way interaction between object-shadow separation and luminance for each shadow shape. For both figures, elevation change is plotted on the vertical axis, with luminance plotted on the horizontal axis. Each triad of bars represents the three object-shadow separation distances. The main point to note in Figures J-3 - J-5 is that, regardless of the shadow shape, the effect of separation is the same for positive and negative shadow luminance. The three-way interaction results from the fact that the magnitude of the effect varied non-systematically among luminance and shadow shape. For example, note the change in elevation for small separations with negative and positive luminance for the complex shadow in Figure J-3, versus the same information for the sphere shadow in Figure J-4. For complex shadows, the change in elevation is larger for negative than for positive luminance. For sphere shadows, however, the change in elevation is smaller for negative luminance than for positive. Such unsystematic variations are uninterpretable.

Figure J-3. Interaction of luminance and separation distance for the complex shadow shape.

Figure J-4. Interaction of luminance and separation distance for the sphere shadow shape.

Figure J-5. Interaction of luminance and separation distance for the simplified shadow shape.

There was also a significant interaction between object shape and luminance, univariate $F(1, 22) = 5.81$, $p < .03$, which was also uninterpretable. Object shape and

luminance also interacted with shadow shape, univariate $F(2, 44) = 4.46, p < .02$. As Figures J-6 and J-7 show, variations in luminance are non-systematic for each of the object shapes. In some cases, positive luminance results in slightly higher elevation change than negative luminance. In other cases, the reverse is true.

Figure J-6. Interaction between object shape and luminance with the complex object.

Figure J-7. Interaction between object shape and luminance with the sphere.

Repeated exposure to the images had an effect on subjects ratings of object elevation, as indicated by the significant main effect of replications, univariate $F(1, 22) = 6.26, p < .03$. Subjects rated the elevation of objects slightly higher in their first viewing of the images ($M = 60.2$) than in their second ($M = 57.1$). Replications did not have any effect on other combinations of variables, with one exception. One four-way interaction between replications, experiment order, object, and separation was statistically significant, univariate $F(2, 44) = 3.73, p < .04$. The results of this four-way interaction, shown in Figures J-8 through J-11, were non-systematic and uninterpretable.

Figure J-8. Interaction between replications, experiment order, objects, and separation. First experiment order with the complex object.

Figure J-9. Interaction between replications, experiment order, objects, and separation. Second experiment order with the complex object.

Figure J-10. Interaction between replications, experiment order, objects, and separation. First experiment order with the sphere object.

Figure J-11. Interaction between replications, experiment order, objects, and separation. Second experiment order with the sphere object.

The data also showed that there were no differences between the two experiment orders, univariate $F(1, 22) = 1.43$, $p > .2$. There were, however, a number of interactions with experiment order. Experiment order interacted with objects, multivariate $F(1, 22) = 15.16$, $p < .005$ (shown in Figure J-12), with separation, multivariate $F(2, 44) = 33.83$, $p < .001$ (shown in Figure J-13), with luminance, multivariate $F(1, 22) = 5.79$, $p < .03$ (shown in Figure J-14).

Figure J-12. Interaction of experiment order with object shape.

Figure J-13. Interaction of experiment order with separation.

Figure J-14. Interaction of experiment order with luminance.

Experiment order also interacted with shadows and separation, univariate $F(4, 88) = 2.76, p < .04$, shown in Figures J-15 and J-16, and with separation and luminance, univariate $F(2, 44) = 4.29, p < .03$, shown in Figures J-17 and J-18.

Figure J-15. Interaction of experiment order with shadow shape and separation for the first experiment order.

Figure J-16. Interaction of experiment order with shadow shape and separation for the second experiment order.

Figure J-17. Interaction of experiment order with separation and luminance for the first experiment order.

Figure J-18. Interaction of experiment order with separation and luminance for the second experiment order.

Discussion

The results obtained in Experiment 4 suggests differences in the apparent baseline elevation of objects, on the basis of object shape. There was a tendency for subjects to rate the elevation change of the complex object higher than the sphere object. This effect appears to be the result of some subjects perceiving the sphere as decreasing in elevation when a cast shadow was added to the scene. This effect was rarely encountered for the

complex object, however. Most subjects perceived an increase in elevation of the complex object when a shadow was added. This interpretation is consistent with comments from subjects, who occasionally noted that the sphere appeared to float above the surface when no shadow was present, while the complex object appeared to rest on the surface of the ground. Thus, the addition of a shadow to the sphere object could result in the appearance of the shadow decreasing in elevation. The addition of a shadow to the complex object, however, tended to increase the apparent elevation (since it could not be perceived as decreasing in elevation). This differential effect of shadows on the two objects reiterates the ambiguous elevation of an object when no cast shadow is available.

Appendix K

Lateral positioning results for Experiment 5

Table K-1 shows response frequencies, expressed as percentages of all responses, for the relative proximity of the target objects when the target was presented on the left side of the comparison object. Similarly, Table K-2 shows the response frequencies when the target object was presented on the right side. As the tables reveal, the relative lateral positioning of the two objects had no notable effects on proximity decisions of subjects. In other words, results were comparable regardless of whether the target object appeared to the right or the left of the comparison object.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	27%	24%	49%	192
Simplified Shadow at Top	44%	25%	31%	192
Simplified Shadow at Bottom	13%	21%	66%	192

Table K-1. Frequency counts for proximity decisions (all objects included).
Target object presented on left.

<u>Shadow Conditions</u>	<u>Nearer</u>	<u>Same</u>	<u>Further</u>	<u>Total Responses</u>
Two Correct Shadows	21%	27%	52%	192
Simplified Shadow at Top	46%	25%	29%	192
Simplified Shadow at Bottom	15%	18%	66%	192

Table K-2. Frequency counts for proximity decisions (all objects included).
Target object presented on right.