## 1 Introduction

Gibson (1950) described an important source of information available in the projection of a 3-D scene for the perception of the location of objects in that scene, which he referred to as optical contact. Optical contact describes the contact in a 2-D projection of a 3-D scene between the image of an object and the image of a background surface.

information from shadows is integrated with these other sources of information in determining the perceived positions of objects in a scene. This is the purpose of the present study.

Shadow not only affects the perception of 3-D shape (eg Ramachandran 1988), but also affects object recognition (Braje et al 1998, 2000; Castiello 2001). Castiello (2001) asked observers to recognize familiar objects, such as an apple, a banana, a bottle, etc, while changing the presence, location, and shape of cast and attached shadows. He found that shadows increased response time if the cast shadows and attached shadows were made incongruent by deriving them from different light sources. These results indicated that correct shadow information favored the perception of an object in 3-D space, but this perception could be impaired by incorrect or conflicting shadow information. In studies of the relation of shape to shadows, Knill et al (1997) applied a systematic analysis of local geometric structure of shadows on continuous surfaces. Their results showed that intrinsic shadows could be informative about the properties of 3-D objects, such as illumination direction and surface structure.

In a developmental study of the perception of shape and distance from shadows, Yonas et al (1978) found that young children were able to judge the shapes of objects from cast shadows. Children aged 3 and 4 years were shown picture cards with an ellipse on the wall and an ellipse on the ground plane, each of which represented a circle. When shadow information was provided, shape judgments were improved and perceived distance was affected by the location of shadow. Comparing the effectiveness of shadows to other cues, Wanger et al (1992) found that shadows have a dominant role in visual perception of computer-generated images relative to perspective, texture, reference frames, and motion. Shadows play an important role in determining perceived distance not only in monocular vision but also in binocular vision. Puerta (1989) found

The clearest demonstrations of the importance of shadow in the perception of dynamic 3-D displays are found in research by Kersten and his colleagues. Kersten et al (1996) introduced a dramatic phenomenon called ``illusory motion from shadow'', in which the displacement of the shadow relative to a stationary square induced a strong perception of the motion of the square in depth. Kersten et al (1997) employed a ``ball in a box'' display, in which observers judged the height of a ball moving diagonally across the bottom of a box. Variations in the motion trajectory of the object's cast shadow floating object when its appearance was fully compatible with that of a shadow, that is when it had zero thickness and was dark rather than textured.

Proximity should be less important in associating an object with a shadow than in associating an object with a second object in a scene, as long as there is common motion between the object and shadow. This hypothesis was considered in the second

2.1.3 Design. The independent variables were whether the scene was in motion or stationary, whether the bottom cylinder was textured or shaded, and the thickness of the bottom cylinder (0/3, 1/3, 2/3, or 3/3 that of the top cylinder). The twenty-four observers were divided into four groups and the first two independent variables were run as between-subjects variables, to avoid any possible influence of viewing displays in one combination of motion and shading conditions on judgments in another combination of conditions. The thickness variable was run within subjects. Each observer also responded to a control condition in which the gap between the two cylinders was held constant, but the height of the top cylinder was allowed to vary. The constant-height and constant-gap conditions were run in separate blocks for each group. The order of the blocks was counterbalanced across observers. Each block contained six replications of each of the four thickness levels. The 24 trials in each block were randomly arranged for each observer. A practice block, with the same conditions as the first block but in a different random order, preceded the first block.

2.1.4 Apparatus. A Pentium 4 2-GHz computer displayed the stimuli on a 21-inch (53-cm) flat-screen CRT monitor at a resolution of 1024 (horizontal) $\times$ 768 (vertical) and a refresh rate of 85 Hz. The experiment was carried out in a darkened room. Observers viewed the displays binocularly from a distance of 85 cm through a 19-cm-diameter collimating lens with a focal length of 75 cm, with their heads stabilized by a chin-rest and head-rest. A black viewing hood was placed between the collimating lens and the monitor, limiting the field of view to the display area, and black cloth separated the observer from the apparatus to ensure that the observer would not see the location of the monitor. Responses were made with a Microsoft SideWinder joystick.

2.1.5 Procedure. The observers' task was to adjust the red marker on the track on the right side of the scene, as shown in figure 1, until it matched the distance of the front surface of the cylinder. Observers pressed the trigger button on the joystick when they were satisfied with their response.

### 2.2 Results and discussion

Judged cylinder position as a function of bottom-cylinder thickness is shown in figure 3a. The observed data are the mean judged distances of the front edge of the top object for the six observers, for the conditions with two textured cylinders and with one textured and one dark, shaded cylinder. The graphs also show the optical-contact positions in the image for the top ain o4ei413(e(u)2(t)-7(a)-8o)-551aosc fgeb(in
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shaded and thickness ($F_{3\ 60} = 3.56$, $p < 0.05$). As shown in figure 3a, there was a greater

A three-way ANOVA showed a significant main effect for motion versus stationary ($F_{1\ 20} = 12.02$, $p < 0.01$). The main effect for textured versus shaded was not significant ($F_{1\ 20} = 3.07$, $p > 0.05$). The main effect of thickness was significant ($F_{3\ 60} = 15.94$, $p < 0.01$). This would be expected because the height of the top cylinder, and therefore its optical-contact position, varied with thickness in the constant-gap control displays. There were no significant interactions. Although the main effect of textured versus shaded was not significant in the ANOVA, figure 3b shows that judged distance was greater for the textured stimuli than for the shaded stimuli for all eight combinations of motion versus stationary and thickness.

Overall, judged distances were affected by variations in whether the lower object was a textured or a dark, shaded object, regardless of its thickness. Variations in thickness of the lower object, on the other hand, had little effect on the judged distance of the floating object, with one exception: for the dark lower object there was a drop in the perceived distance of the floating object when the thickness of the lower object was reduced to zero, that is when both shading and thickness indicated that the lower object was a shadow.

## 3 Experiment 2: Variation in gap size

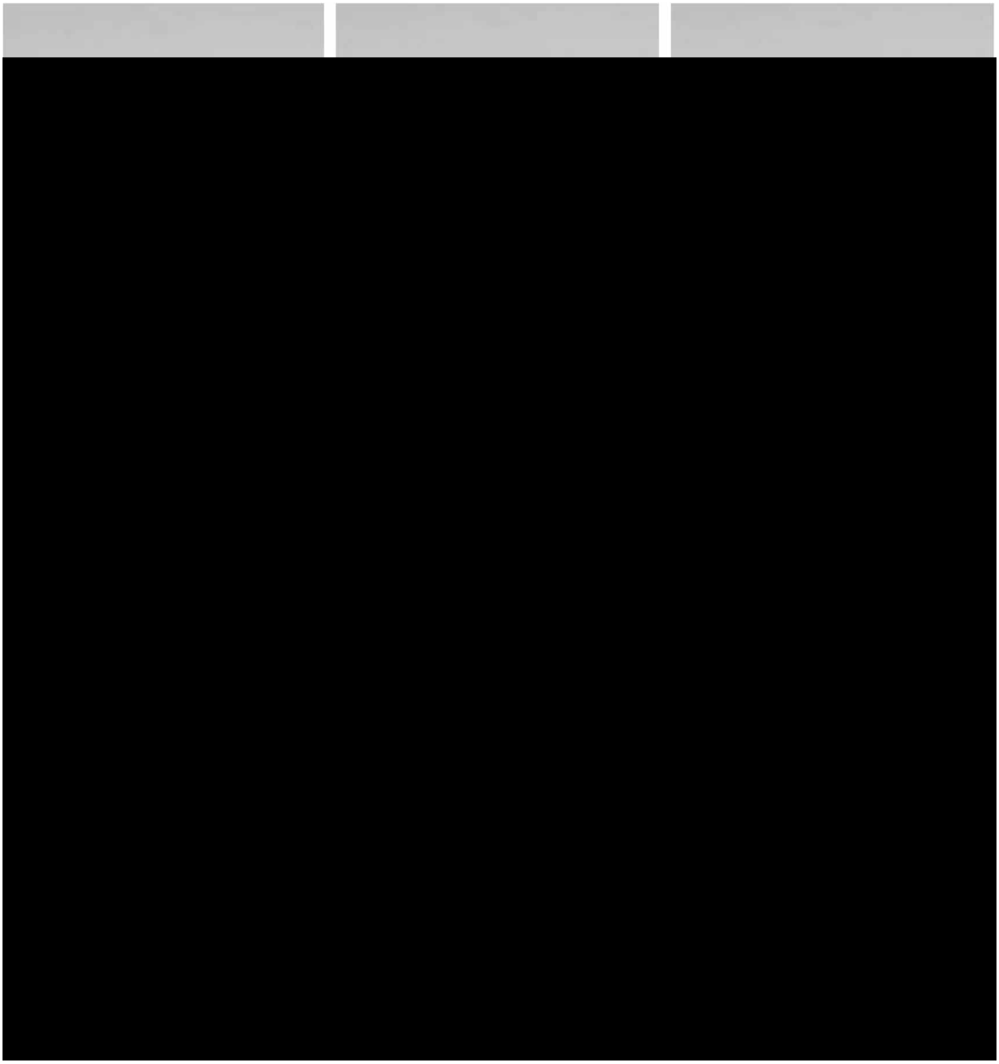
In experiment 1, small variations in the gap between the cylinders were introduced in the main experiment as a result of the variations in the thickness of the bottom cylinder, with the top cylinder kept at a constant height. These variations had little effect on the judgments. The purpose of experiment 2 was to determine whether larger variations in gap size would reduce the tendency to group two textured cylinders in a scene, but would not affect the grouping of one cylinder with a shadow.

### 3.1 Method

3.1.1 Observers. The observers were twenty-four students from the University of California at Irvine. All observers had normal or corrected-to-normal visual acuity and were naïve about the purpose of the experiment. They received extra credit in a psychology course for participating.

3.1.2 Stimuli. The background scene was the same as in experiment 1. The top cylinder was the same projected height and diameter as the top cylinder in experiment 1. The bottom object was either an identical cylinder or a shadow. The top cylinder was either 18 cm, 27 cm, or 36 cm above the ground, or, equivalently, above the shadow. The gap between the top cylinder and the bottom cylinder was 9 cm, 18 cm, or 27 cm. This set of values allows us to compare either conditions in which the distance from the top cylinder to the ground is equal or conditions in which the gap size is equal. Figures 4a ^ 4c show the three cylinder-height conditions for two cylinders and figures 4d ^ 4f show the three cylinder-height conditions for a cylinder and shadow. In the motion conditions, the top cylinder moved rigidly with the bottom cylinder or the shadow.

3.1.3 Design. The independent variables were whether the scene was in motion or stationary, whether the bottom object was a cylinder or a shadow, and the height of the top cylinder above the ground (18 cm, 27 cm, or 36 cm). The first two variables were run between subjects (to avoid any possible influence of viewing displays of one type on responses to displays of another type) with six observers in each condition; the third variable was run within subjects.suthai[(6u.4w)-452((ar)-3460(su60(was)-40Ad3nm)-



(d) (e) (f)

Figure 4. Examples of displays with two cylinders [(a) ^ (c)] and one cylinder and a shadow [(d) ^ (f)], with variations in the height of the top object.

### 3.2 Results and discussion

Figure 5 shows judged distance as a function of the height of the top cylinder, for the conditions with two cylinders and with one cylinder and a shadow, in the motion and stationary displays. In the motion displays, the judged distances fell between the optical-contact position of the top cylinder and the optical-contact position of the bottom cylinder or shadow. They were closer to the top-cylinder position when the bottom object was a cylinder and closer to the bottom-object position when it was a shadow. The effect of the height of the top cylinder was thus larger in the two-cylinder case than in the cylinder-and-shadow case. The results are similar for the stationary displays, except that there was a greater effect of the height of the top cylinder, when the bottom object was a shadow, for the stationary displays than for the motion displays. A three-way ANOVA showed significant main effects for motion versus stationary ($F_{1,20} = 10.13$, $p < 0.01$), two cylinders versus cylinder plus shadow ($F_{1,20} = 10.20$, $p < 0.01$), and cylinder height ($F_{2,40} = 54.39$, $p < 0.01$). The interaction of motion versus stationary and cylinder height was significant ($F_{2\,40} = 8.02$, $p < 0.01$). The slopes of the two curves in figure 4 indicate that the motion displays were less affected by the height of the top cylinder. This suggests that common motion can substitute for proximity in grouping the two cylinders, or the cylinder and the shadow. The interaction of two cylinders versus one cylinder plus shadow with gap was also significant ($F_{2\,40} = 11.14$, $p < 0.01$). This interaction reflects a larger effect of cylinder height for two cylinders than for one cylinder plus a shadow, suggesting that grouping by proximity is less important when matching a shadow with an object than when grouping two objects.

## 4 Experiment 3

In experiment 2, when there was one cylinder and a shadow which had the appropriate size and motion in the scene, judged distance of the cylinder was very close to the distance of the shadow. The same result might be expected if the size or motion of the shadow did not match that of the cylinder (Kersten et al 1997). If there is more than one potential shadow present, however, the perception of the distance of the cylinder would depend on which, if any, of the shadows was attributed to the cylinder. In this experiment we presented three alternative shadows with each cylinder, with the shadows varying in size and speed.

### 4.1 Method

4.1.1 Observers. The observers were nine students from the University of California at Irvine. All observers had normal or corrected-to-normal visual acuity and were naïve about the purpose of the experiment. They received extra credit for participating in the experiment.

4.1.2 Stimuli. The background scene was the same as in experiments 1 and 2. Three dark circular patches (elliptical in the image) were placed at simulated distances of projected sizes and three possible projected speeds resulted in 9 conditions, as shown in table 1. In only three of these conditions, both the projected size and speed of the cylinder were consistent with one of the three shadows (with a light source assumed directly overhead at a great distance). In the other conditions, either the size or speed was consistent with one of the shadows. The optical-contact position of the cylinder was kept constant at 27.5 m. The scene and the shadows translated horizontally at the same speed as in experiments 1 and 2.

4.1.3 Design. There were two independent variables: the size of the cylinder, which was matched to one of the three shadows; and the speed of the cylinder, which was matched to the speed of one of the three shadows. The two variables were run within observers. Each observer responded to 6 repetitions of each of the 9 conditions. The 54 trials were divided into two blocks, with 3 repetitions of each condition randomly ordered in each block. The two experimental blocks were preceded by a practice block consisting of 3 replications of each condition.

4.1.4 Apparatus and procedure. The apparatus and procedure were the same as in experiments 1 and 2.

### 4.2 Results and discussion

Judged distance as a function of the projected speed of the top cylinder and the projected diameter of the top cylinder, averaged across observers, is shown in figure 7. These results indicate consistent effects of both cylinder speed and cylinder size, with cylinder speed having the larger effect. A two-way ANOVA showed significant main effects for speed ($F_{2\ 16} = 24.0$, $p < 0.01$), and for projected size ($F_{2\ 16} = 14.6$, $p < 0.01$). The interaction was not significant (

## 4.3 Control experiment

than an assumption of rigid motion among objects.[1] The relation between studies with multiple objects moving together and studies with moving shadows thus appears to be based on the use of a common-motion constraint in both cases, one relying on an assumption of rigidity or quasi-rigidity and the other relying on an assumption of a stationary light source.

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References

Braje W L, Kersten D, Tarr M J, Troje N F, 1998 ``Illumination effects in face recognition'' Psychobiology 26 371 ^ 380

Braje W L, Legge G E, Kersten D, 2000 ``Invariant recognition of natural objects in the presence of shadows'' Perception 29 383 ^ 398

Braunstein M L, Andersen G J, 1984 ``Shape and depth perception from parallel projections of three-dimensional motion'' Journal of Experimental Psychology: Human Perception and Performance 10 749 ^ 760

Castiello U, 2001 ``Implicit processing of shadows'' Vision Research 41 2305 ^ 2309

Gibson J J, 1946 ``Perception of distance and space in the open air'', in Motion Picture Testing and Research Ed. J J Gibson (AAF program Report # 7), reprinted in Readings in Perception Eds D C Beardslee, M Wertheimer (1958, Princeton, NJ: Von Nostrand)

Gibson J J, 1950 The Perception of the Visual World (Boston, MA: Houghton Mifflin)

Kersten D, Knill D C, Mamassian P, Bülthoff I, 1996 ``Illusory motion from shadow'' Nature 379 31

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