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Scene layout from ground contact, occlusion, and motion parallax

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An important factor in determining perceived scene layout is optical contact between objects and the ground surface ("ground contact"). The relation between ground contact and occlusion was investigated in four experiments with stationary and motion parallax scenes containing a pole that occluded or was occluded by one or more cylinders. Some judgements were inconsistent with occlusion in stationary scenes, but judgements were consistent with occlusion in motion parallax scenes. When the range of object positions consistent with occlusion did not include the positions specified by ground contract or by motion parallax, the ground contact and motion parallax information still had a quantitative effect on the perceived position of the object within the range consistent with occlusion. These results demonstrate a cooperative interaction between ground contact, occlusion, and motion parallax in determining perceived layout in 3-D scenes.

Although the importance of a continuous ground surface in the perception of the visual world was described by Alhazen (c. 1024/1989) almost 1000 years ago and by Gibson (1946/1958) 60 years ago, there was little research on the role of the ground surface in the perception of 3-D scenes until quite recently (Feria, Braunstein, & Andersen, 2003; He, Wu, Ooi, Yarbrough, & Wu, 2004; Meng & Sedgwick, 2001, 2002; Ni, Braunstein, & Andersen, 2005; Ooi, Wu, & He, 2001; Sedgwick, 1986; Sinai, Ooi, & He, 1998; Wu, Ooi, & He, 2004). Gibson (1950) suggested that when there is no information from relative motion or stereoscopic depth, the perceived distance of an

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object is mainly determined by its "optical contact" position—where the object contacts the ground surface in the visual projection.

Meng and Sedgwick (2001, 2002) provided important information about the role of optical contact with a ground surface in determining the perceived positions of objects in a static scene. They found that the judged position in a scene of an object resting on a platform was determined by a "mediated" contact relation, based on the optical contact of the object with the platform and the optical contact of the platform with the ground. An object on a floating platform was thus perceived as further back in the scene because the image of the platform contacted the ground at a more distant location.

While direct or mediated ground contact appears to determine perceived layout in static scenes, a combination of ground contact and motion parallax can produce ambiguous information about layout in a dynamic scene. (We use "ground contact" to mean "optical contact with the ground surface", referring to the position on the ground at which the projection of an object is located in the image, not to physical contact in the 3-D scene.) A floating object moving rigidly with the ground surface may appear to be lying on the ground and moving relative to the ground or floating above the ground and moving rigidly with the ground. Using computer-generated objects combined with a movie of a real-world scene, Ni et al. (2005) found that ground contact information continued to be dominant in determining perceived layout with a single moving object in a moving scene, but motion parallax was given increasingly more weight with the addition of a second object. Perceived layout was determined by motion parallax when three objects moved rigidly with the scene. Ni et al. (2004) found that a moving shadow had greater influence than a second object in determining perceived layout. This result was consistent with Kersten, Mamassian, and Knill's (1997) finding that the perceived motion of an object in a 3-D scene is determined by the motion of its cast shadow.

Ground contact information, whether in a static or dynamic scene, provides ambiguous information about layout because an object with a given ground contact position may be perceived as floating above the ground or lying on the ground at a greater distance. Our previous studies showed that judgements can be biased towards the floating interpretation with the addition of motion, especially of multiple objects, and even more so with the addition of a cast shadow. Another type of information that can influence perceived layout, and is particularly suited to resolving ambiguities in depth order, is occlusion (see Cutting & Vishton, 1995, for a classification of depth cues, and Howard & Rogers, 2002, pp. 385–392, for a review of occlusion research). Occlusion, for example, can resolve the depth order ambiguity in a parallel projection of a rotating sphere (Braunstein, Andersen, & Riefer, 1982) even when present only in dynamic views (Andersen & Braunstein, 1983).

In a recent study of the effect of occlusion of a portion of the ground surface on perceived distance (He et al., 2004) a black occluding box was placed on the ground between the observer and a target. Estimates of the perceived distance of the target were obtained using a variety of methods, including distance matching and blindfolded walking. Distance to the target was underestimated when part of the ground surface was occluded.

In this paper, we report four experiments that investigate how occlusion affects the perception of layout in a 3-D scene. We expected occlusion to provide ordinal information about depth order (Cutting & Vishton, 1995). Our purpose was to examine the interaction of occlusion with information that provides a quantitative indication of layout, specifically ground contact and motion parallax. Two possible interactions were considered for cases in which the position of an object specified by ground contact or motion parallax was outside of the range specified by occlusion. The first possibility is that ground contact or motion parallax, if it specifies an object position inconsistent with occlusion, will no longer affect the perceived position of the object (a veto relationship as described by Bülthoff & Mallott, 1988). The second possibility is that the information that is inconsistent with occlusion—ground contact or motion parallax—will have a quantitative effect on the perceived position of the object, even though the perceived position will fall within the range specified by occlusion and will not be consistent with the ground contact or motion parallax information.

As in our previous research, we superimposed simulated objects on a movie of a real scene in order to have both precise control over the objects being judged and maximum realism in the background scene. In the first two experiments, we studied the role of occlusion in disambiguating ground contact information in stationary and moving 3-D scenes. The observer's task in each experiment was to judge the location in depth of a cylinder positioned against a grass background. Occlusion was introduced by placing a simulated vertical pole in the scene so that it either occluded or was occluded by the target cylinder. Occlusion was expected to affect the perceived distance of the cylinder in both stationary and moving scenes. We were especially interested in determining whether, in a motion parallax scene, the occlusion information would constrain the possible perceived locations of the cylinder, with the combination of ground contact and motion parallax information providing a specific perceived distance within those constraints. In the third experiment we varied the ground contact position of the vertical pole which either occluded or was occluded by the target cylinder. We expected an effect of the position of the vertical pole on the perceived distance of the cylinder, even for variations in position that did not alter the depth order of the pole and the cylinder. In the last experiment, we introduced a second cylinder which moved rigidly with the first cylinder. We expected an influence of the second cylinder on the judged position of the first cylinder, even when occlusion indicated that the two cylinders could not be at the same distance.

EXPERIMENT 1: OCCLUSION IN A STATIONARY SCENE

The purpose of Experiment 1 was to investigate the relation between occlusion and ground contact in determining perceived layout in a stationary scene.

Method

Observers. The observers were 12 students from the University of California, Irvine. All had normal or corrected-to-normal visual acuity and all were naive about the purpose of the experiment. The observers received extra credit in a psychology course for participating.

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

Stimuli. Each display consisted of a computer-generated cylinder, a computer-generated vertical pole, and a computer-generated track with a red marker, superimposed on a colour photograph of an actual 3-D scene. The photograph was taken with a Kodak DC260 digital camera with a 35 mm equivalent lens and cropped from its original size of 1536 $\times$ 1024 pixels to 1024 $\times$ 768 pixels, with the original pixel aspect ratio kept unchanged. An example of a display with the cylinder occluding the pole is shown in Figure 1. The simulated ground contact position of the cylinder was either 14.25 m (near condition) or 22.35 m (far condition) from the observer. The cylinder had the same projected diameter (3.4 cm) in both conditions. Each display contained a single cylinder either with the pole present or absent. If the pole was present, either it partially occluded or it was partially occluded by the cylinder. The projected height of the pole was 5.6 cm. The ground contact position of the pole was 8.85 m from the observer in the near position and 14.25 m in the far position. Figure 2 shows the six

Figure 1. An example of a display with the cylinder occluding the pole. The subjects were required to adjust the marker along the textured track on the right side, until it matched the perceived distance of the front edge of the cylinder. [Visit the journal website to view this and the following figures in colour in the online version of this paper.]

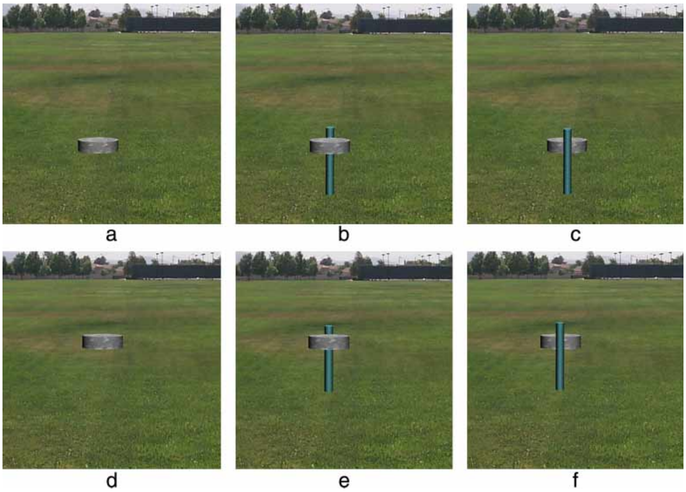

Figure 2. The display types in Experiment 1. The pictures were cropped for this figure from the full scene that was actually displayed (Figure 1). Panels a–c show the near ground contact position (14.25 m for the cylinder and 8.85 m for the pole). Panels d–f show the cylinder and pole in the far ground contact position (22.35 m for the cylinder and 14.25 m for the pole).

combinations of scene position and pole condition. (The projected sizes are measured at the monitor and do not take into account the 19% magnification of the collimating lens.) At the observer's distance of 85 cm from the monitor, taking into account the lens magnification, the visual angles subtended by distances in the scene were approximately 20% greater than the visual angles that would be subtended by these distances for an observer standing at the position of the camera in the real-world scene.

Design. The independent variables were display type (cylinder only, cylinder occluding pole, and cylinder occluded by pole) and ground contact position (near and far). Both variables were run within observers, with display type run in separate blocks and ground contact position randomized within each block. Each block contained 10 repetitions of each condition, for a total of 20 trials. The order of the three blocks was counterbalanced in a Latin square. The first block was preceded by a practice block consisting of half of the trials in the first block.

Procedure. The observers' task was to judge the distance to the centre of the cylinder. As in previous studies (Meng & Sedgwick, 2001, 2002; Ni et al., 2005), observers adjusted the red marker on the track on the right side of the scene (shown in Figure 1) until it appeared to match the distance of the cylinder. The position of the red marker was adjusted with a joystick. When satisfied with their responses, observers pressed the trigger button on the joystick to advance to the next trial.

Results and discussion

Figure 3 shows the mean judged distance of the cylinder averaged across observers for the three display types and two ground contact positions. An ANOVA showed significant main effects for display type, $F(2, 22) = 6.39$, $MSE = 7.74$, $p < .01$, and scene position, $F(1, 11) = 462.87$, $MSE = 2.95$, $p < .01$, and a significant interaction between these two variables, $F(2, 22) = 7.25$, $MSE = 1.05$, $p < .01$. A Tukey HSD test found significant differences, $p < .05$, between all three occlusion conditions for the far scene position. Comparing the three occlusion conditions for the near scene position, only the difference between the cylinder only and the cylinder occluding the pole conditions was significant.

As can be seen in Figure 3, the judged distance of the cylinder was greater when it was occluded by the pole than when it occluded the pole. (This difference was significant only for the far scene position.) This was not surprising since occlusion has been shown to provide qualitative depth information (reviewed by Howard & Rogers, 2002). There were two

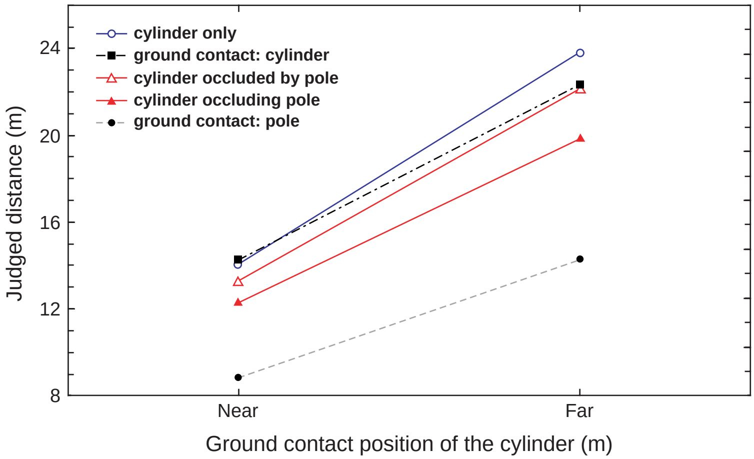

Figure 3. Results in Experiment 1. The solid lines show judged distances for the cylinder. The dashed lines show the ground contact positions of the cylinder and the pole.

unexpected results, however. When the cylinder was behind the pole, it was judged closer to the front of the scene than when it was presented by itself. (This difference was significant only for the far scene position.) Occlusion of the cylinder by the pole would not be expected to make the pole appear closer, so it seems likely that the cylinder was perceived as closer to the pole as a result of the equidistance tendency (Gogel, 1965). The equidistance tendency is "the tendency, in the absence of effective distance cues, for objects (or parts of objects) to appear equidistant" from the observer (Gogel, 1969, p. 342). An alternative explanation is that the optical contact between the pole and the front of the cylinder suggested that they were in physical contact. This optical contact information would indicate that the cylinder was above the ground, conflicting with the indication from optical contact between the cylinder and the ground that the cylinder was lying on the ground behind the pole.

Even more surprising was the finding that when the cylinder occluded the pole, it was judged to be further back than the ground contact position of the pole. This result was found for each of the 12 observers. Since the cylinder was clearly seen in front of the pole in this condition, this finding suggests that observers viewing a stationary scene may have been able to focus on the ground contact position of the cylinder and ignore the occlusion relation between the cylinder and the pole, when judging the location in the scene of the occluding cylinder.

EXPERIMENT 2: MOTION PARALLAX AND OCCLUSION

In Experiment 1, the judged distance of the cylinder behind the pole was closer than its ground contact position, indicating that the effect of ground contact in that condition was modified by the tendency to perceive objects that are adjacent in the image as adjacent in depth. We expected that relative motion between the cylinder and the pole in motion parallax scenes would result in a perceived separation in depth, allowing the cylinder behind the pole to be perceived closer to its ground contact position. A more important reason for introducing motion parallax, however, was to determine whether observers would judge the distance of the cylinder according to the quantitative depth information provided by motion, within the range of distances consistent with the occlusion information.

Method

Observers. The observers were 11 students from the University of California, Irvine. All had normal or corrected-to-normal visual acuity and were naive about the purpose of the experiment. The observers received extra credit in a psychology course for participating. None had participated in the first experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. Each display consisted of a computer-generated cylinder, a vertical pole, and a track with a red marker, superimposed on a background movie of an actual 3-D scene. The background movie consisted of 50 photographs taken at fixed positions along a horizontal track that were space according to a sinusoidal function, with the larger separations in the centre of the track and the smaller separations at the ends. This was intended to approximate the motion of an observer moving his or her head back and forth horizontally. The camera motion in one direction was approximately 90 cm and was displayed in 2 s. The method of photography and the cropping of the photographs were the same as in Experiment 1. The photograph used in Experiment 1 was frame 25 of the 50 used in the motion picture.

The locations of the cylinder and pole were the same as in the far condition in Experiment 1, shown in Figure 2d–f. The simulated position of the pole was always 14.25 m from the observer and the ground contact position of the cylinder was always 22.35 m in distance. The pole translated horizontally at a speed consistent with rigid motion with the scene at a distance of 14.25 m. The cylinder translated either at a speed consistent with a distance of 7.05 m or 22.35 m. The first speed was consistent with rigid

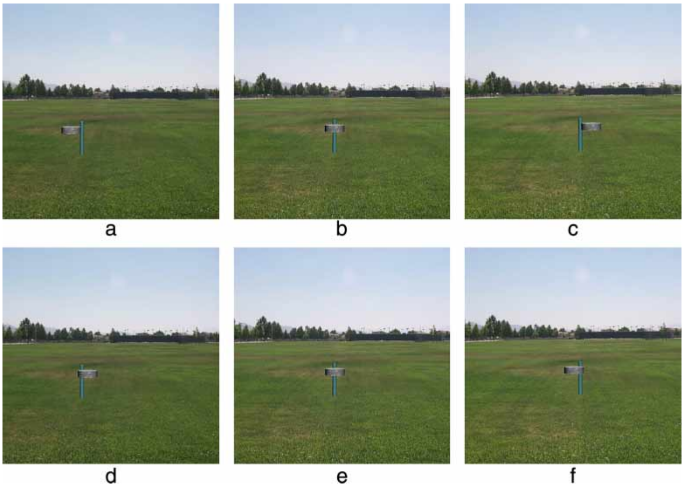

Figure 4. Examples of displays with the cylinder occluding the pole from Experiment 2. Panels a–c show frames 1, 26, and 50 from a display with motion parallax indicating a distance of 7.05 m. Panels d–f show these frames for a 22.35 m distance. Adjacent pairs of images can be viewed stereoscopically using crossed fusion for a general indication of the relative depths associated with occlusion and motion parallax.

motion of an object floating above the ground; the second speed was consistent with rigid motion of an object on the ground. Figure 4 shows three frames from each type of display in which a pole was present.

Design. The independent variables were the display type (cylinder only, cylinder occluding pole, and cylinder occluded by pole) and the cylinder distance indicated by the translation speed (7.05 m or 22.35 m). Each condition was repeated 10 times in a random sequence. The 60 trials were divided into two blocks, preceded by a practice block consisting of half of the trials in the first block.

Procedure. The procedure was the same as in Experiment 1.

Results and discussion

Figure 5 shows the judged distance of the cylinder averaged across the 11 observers. An ANOVA found significant main effects for display type, $F(2, 20) = 43.07$, $MSE = 6.92$, $p < .01$, and speed, $F(1, 10) = 13.22$, $MSE = 7.56$, $p < .01$, and a significant interaction, $F(2, 20) = 10.37$, $MSE = 2.29$, $p < .01$. Tukey HSD tests found all comparisons among the six cells in the design to be significant, $p < .05$, except for the comparisons between the

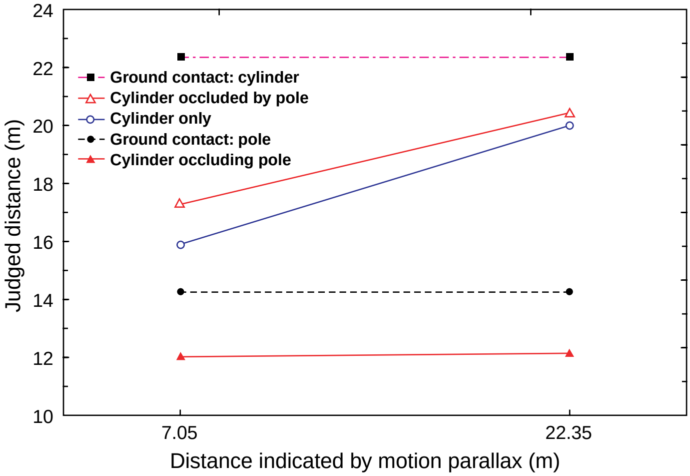

Figure 5. Results in Experiment 2. The solid lines show mean judgements. The dashed lines show simulated values.

cylinder only and the cylinder occluded by the pole conditions (at both levels of motion parallax) and between the two levels of motion parallax with the cylinder occluding the pole.

As can be seen in Figure 5, when the cylinder was in front of the pole, the judged distance did not change according to the cylinder speed. There was thus no apparent effect of variations in the motion parallax information for relative distance in that condition. When the cylinder was occluded by the pole, or presented without the pole, its judged distance was affected by its speed. In contrast to the results of Experiment 1, judged distance was greater for the cylinder occluded by the pole than for the cylinder presented without the pole. This result was found for 10 observers. (The remaining observer judged the distance of the cylinder to be the same as that of the pole in this condition.) This suggests that motion was effective in overcoming the tendency to judge the cylinder and pole as adjacent in depth. It can also be seen in Figure 5 that, in contrast to Experiment 1, when the cylinder occluded the pole its position along the ground was judged to be closer than the position of the pole. This suggests that the possibility of ignoring the ground contact position of the pole is reduced when relative motion between the cylinder and the pole is present in the image, probably because the kinetic occlusion generated in this case is more salient than static occlusion in a stationary scene. Judged depth was greater in the cylinder only condition in Experiment 1 than in Experiment 2. Possibly the inclusion of a closer ground contact position in Experiment 1 led to a contrast effect in that experiment.

CONTROL STUDY

Our interpretation of the results of Experiment 2 is based on the pole serving as a reference position in judgements of the cylinder position. A control experiment was conducted to assure that the judged distance of the pole itself was not altered by whether it occluded or was occluded by a cylinder. We used the same conditions as in Experiment 2, except that only two types of displays were used: A pole occluded by a cylinder and a pole occluding a cylinder. The observers were the same as in Experiment 2. They participated in the control experiment immediately after participating in Experiment 2. They were asked to move the red marker to the perceived distance of the pole, rather than to that of the cylinder. An ANOVA found no significant effects, $F(1, 10) < 1$ for display type, $F(1, 10) < 1$ for cylinder speed, and $F(1, 10) < 1$ for the interaction. The mean judged pole positions for the fast and slow cylinder speeds, respectively, were 14.11 m and 14.16 m for the pole occluding the cylinder and 14.12 m and 14.29 m for the pole occluded by the cylinder.

EXPERIMENT 3: GROUND CONTACT AND OCCLUSION

If the addition to a scene of an occluded or occluding pole has only a qualitative effect on perceived layout (i.e., affects only perceived depth order), then changing the position of the pole in the scene without changing the depth order indicated by occlusion should not affect the perceived position of the cylinder. Alternative possibilities are that the judged position of the cylinder will move towards the occluding or occluded pole, as in the stationary displays in Experiment 1, or that the position of the pole will interact with other layout information by changing the range of distances at which the cylinder can be perceived. In Experiment 3 we varied the position of the pole without changing the depth order indicated by occlusion to examine the quantitative effect of pole position on the judged position of the cylinder.

Method

Observers. The observers were six students from the University of California, Irvine. All had normal or corrected-to-normal visual acuity and all were naive to the purpose of the experiment. The observers received extra credit in a psychology course for participating. None had participated in the first two experiments.

Apparatus. The apparatus was the same as in Experiments 1 and 2.

Stimuli. Each display consisted of a computer-generated cylinder, a vertical pole, and a track with a red marker, superimposed on a background movie of an actual 3-D scene. The background movie was the same as in Experiment 2. The configurations of cylinder position and pole position are shown in Figure 6. The simulated pole position was at one of three distances from the observer: 10.65 m, 12.45 m, or 14.25 m. The ground contact position of the cylinder was always at 22.35 m. The cylinder either occluded or was occluded by the pole. The cylinder's translation speed simulated either a near distance (7.05 m) or a far distance (22.35 m). At the near distance the cylinder's motion was consistent with an object moving rigidly with the scene but floating above the ground.

Design. The independent variables were the display type (cylinder occluding pole or pole occluding cylinder), the distance of the cylinder simulated by motion (7.05 m and 22.35 m), and the pole position (10.65 m, 12.45 m, and 14.25 m). Each condition was replicated six times for a total of 72 trials. The trials were presented in a random order in two blocks, preceded by a practice block consisting of half of the trials in the first block.

Procedure. The procedure was the same as in Experiment 1.

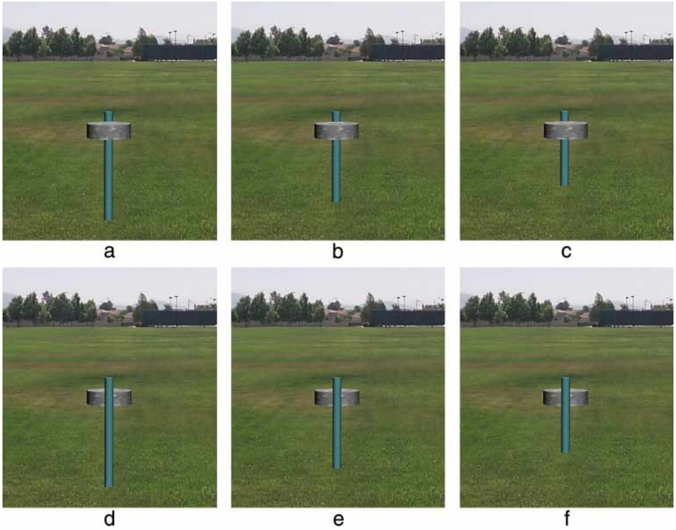

Figure 6. Single frames from displays in Experiment 3. Panels a–c show the three pole positions with the cylinder occluding the pole. Panels d–f show these pole positions with the pole occluding the cylinder. Displays were produced with two cylinder translation speeds for each of these six combinations of pole position and depth order.

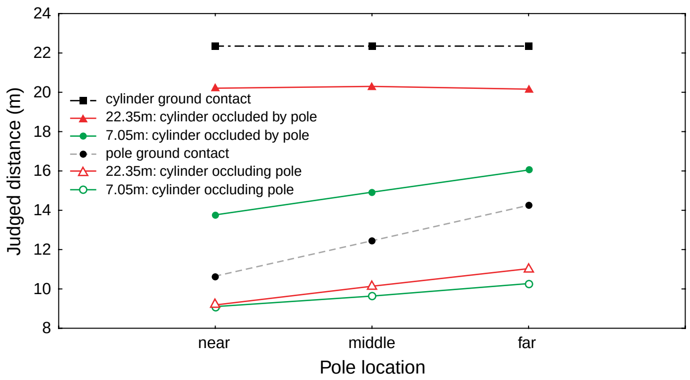

Figure 7. Results in Experiment 3. The solid lines show mean judgements. The dashed lines show simulated values.

Results and discussion

Figure 7 shows the judged distance of the cylinder averaged across observers. An ANOVA found significant main effects for display type (depth order indicated by occlusion), $F(1, 5) = 78.10$, $MSE = 13.57$, $p < .01$, speed, $F(1, 5) = 19.43$, $MSE = 7.68$, $p < .01$, and pole position, $F(2, 10) = 19.39$, $MSE = 0.53$, $p < .01$. A Tukey HSD test for the main effect of pole position showed significant differences, $p < .05$, between all pairs of pole positions. The interaction between display type and speed, $F(1, 5) = 14.4$, $MSE = 7.38$, was also significant, $p < .05$. A Tukey HSD test showed significant differences, $p < .05$, between the two speed conditions only when the cylinder was occluded by the pole. The triple interaction was also significant, $F(2, 10) = 9.52$, $MSE = 0.36$, $p < .01$. Comparisons for pairs of pole locations within each combination of occlusion and speed condition (Tukey HSD test) showed significant differences, $p < .05$, between the near and far pole locations for (a) displays with the cylinder occluding the pole at the 22.35 m distance and (b) displays with the cylinder occluded by the pole at the 7.05 m distance.

The results shown in Figure 7 indicate that occlusion, pole position, and motion parallax all interact with ground contact information to determine the judged position of the cylinder in the scene. With the cylinder occluding the pole, the cylinder was judged closer than the pole position, as would be expected from the depth order information provided by occlusion. This result was found for all six observers at each of the three pole locations. As the pole was moved further back, the judged position of the cylinder increased in distance also, regardless of the distance simulated by motion parallax. This could be due either to the cylinder moving closer to its ground contact position or closer to the position of the pole.

With the pole occluding the cylinder, there was an effect of the pole position only when motion parallax simulated a cylinder position closer than the pole. Under these conditions, the cylinder was judged to be further back than the pole, in accordance with occlusion, but it was judged to be closer to the front of the scene as the pole was moved closer to the front of the scene. This suggests that the contradictory occlusion information, although it limited the perceived cylinder position to positions further back than that specified by motion parallax, did not eliminate the quantitative effect of motion parallax on judged scene position.

An alternative explanation for the judged position of the cylinder moving closer to the pole location when motion parallax indicated that the cylinder was closer to the front of the scene, is that the judged position of the cylinder was affected by the perceived depth adjacency of the cylinder and pole (Gogel, 1965). There are two reasons for rejecting an adjacency explanation in this case. First, the results of Experiments 1 and 2 indicate that an adjacency effect may be present in stationary displays, but is eliminated by relative motion of the cylinder and pole. Second, when motion parallax, ground contact, and occlusion all indicate that the cylinder is behind the pole, there is no effect of the position of the pole.

EXPERIMENT 4: OCCLUSION AND COMMON MOTION GROUPING

Previous studies (Ni et al., 2005) found that when two objects with a common horizontal motion were stacked vertically in a scene, the perceived position of the top object was influenced by the ground contact position of the lower object. The present experiment examines whether a common occlusion relation—both objects occluding or occluded by a pole—strengthens the tendency to group the two objects at a common distance, whereas an inconsistent occlusion relation inhibits such a grouping.

Method

Observers. The observers were six students from the University of California, Irvine. All had normal or corrected-to-normal visual acuity and all were naive about the purpose of the experiment. The observers received extra credit in a psychology course for participating. None had participated in the previous experiments.

Apparatus. The apparatus was the same as in Experiments 1–3.

Stimuli. Each display consisted of two cylinders, a vertical pole, and a track with a red marker, all of which were computer-generated and

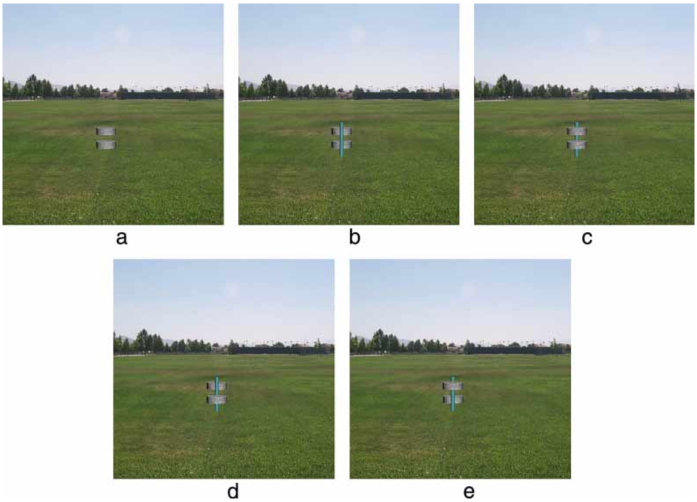

Figure 8. Examples of the five display types in Experiment 4: (a) cylinders only, (b) both cylinders occluded by a pole, (c) both cylinders occluding a pole, (d) top cylinder occluded by pole, bottom cylinder occluding pole, and (e) top cylinder occluding pole, bottom cylinder occluded by pole.

superimposed on a background movie of an actual 3-D scene. The background movie was the same as in Experiments 2–3.

The five configurations of the cylinder positions and the pole position are shown in Figure 8. Examples of three frames from two motion sequences are shown in Figure 9. The simulated pole position was always 14.25 m from the observer. The ground contact position of the top cylinder was 22.35 m from the observer while that of the bottom cylinder was 16.05 m. Either both cylinders occluded the pole, both were occluded by the pole, or one cylinder (the top or the bottom) occluded the pole and the other was occluded by the pole. A condition was included with the two cylinders only. The translation speeds of both cylinders were the same, either simulating a distance from the observer of 7.05 m or 22.35 m. (At 7.05 m the cylinder, if moving rigidly with the ground surface, would be floating above the ground; at 22.35 m it would be lying on the ground.)

Design. The independent variables were the cylinder–pole configurations (both cylinders occluding the pole, both occluded by the pole, the top cylinder occluding the pole and the bottom cylinder occluded by the pole, the top cylinder occluded by the pole and the bottom cylinder occluding the pole, or the pole absent) and the cylinder distance simulated by motion (7.05 m or 22.35 m). Each condition was replicated six times in a random sequence. The 60 trials were divided into two blocks, preceded by a practice block with half of the trials in the first block.

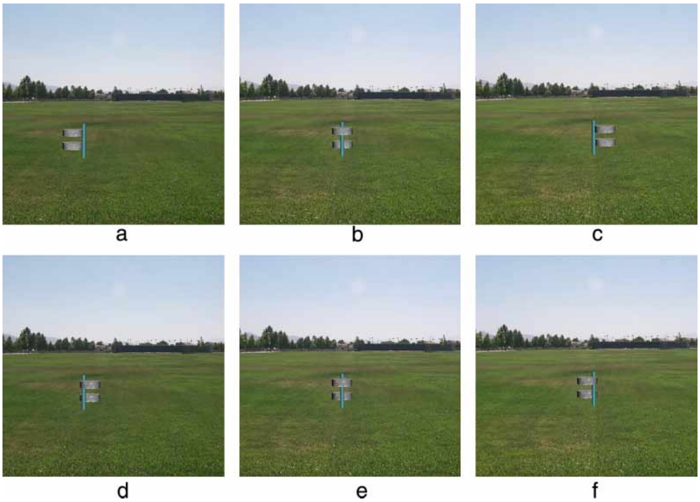

Figure 9. Examples of motion sequences in Experiment 4 for displays with the top cylinder occluding the pole and the bottom cylinder occluded by the pole. Frames 1, 26, and 50 are shown for displays with cylinder distances of 7.05 m (a–c) and 22.35 m (d–f) simulated by motion parallax. Adjacent pairs may be viewed stereoscopically.

Procedure. The procedure was similar to that used in Experiments 1–3, except that observers were asked to judge the distance of the top cylinder in the image.

Results and discussion

Figure 10 shows the judged distances averaged across observers. An ANOVA found significant main effects for display type, $F(4, 20) = 3.89$, $MSE = 6.58$, $p < .05$, and a significant interaction, $F(4, 10) = 3.39$, $MSE = 1.15$, $p < .05$. Comparisons between occlusion conditions, for each of the two speeds in this interaction, were conducted using a Tukey HSD test. For the faster speed, judgements for displays with both cylinders in front were significantly different, $p < .05$, from displays with either both cylinders in back or the target cylinder in front. For the slower speed, judgements for displays with both cylinders in front were significantly different from displays with both cylinders in back, with cylinders only, or with the target cylinder in back. Also for the slower speed, judgements for displays with the target cylinder in front were significantly different from displays with both cylinders in back, with cylinders only, or with the target cylinder in back. The main effect of speed, $F(1, 5) = 3.61$, $MSE = 20.73$, was not significant, $p > .05$.

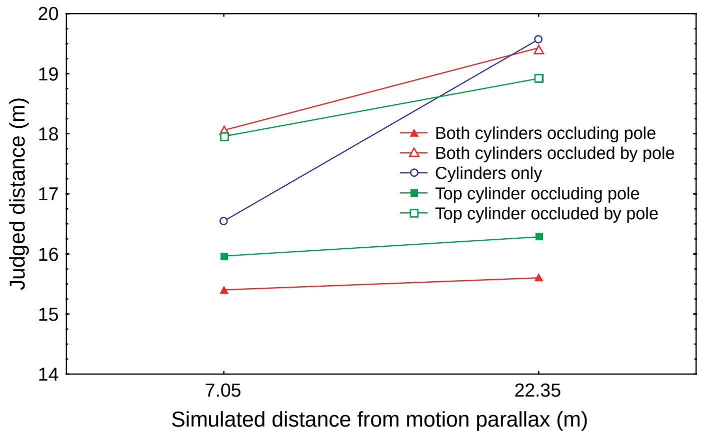

Figure 10. Results in Experiment 4. The ground contact positions were 14.25 m for the pole, 16.05 m for the bottom cylinder, and 22.35m for the top cylinder.

With no occlusion (no pole in the display) there was a clear effect of motion parallax on judged distance. With motion parallax indicating the same distance as the ground contact position of the top cylinder, judged distance was similar to the distance indicated by motion parallax. With motion parallax indicating a distance closer to the ground contact position of the lower cylinder, distance judgements were closer to that position.

The effect of motion parallax was much smaller with a pole present in the display. In this case, the mean judged cylinder positions were just behind the pole when the top cylinder occluded the pole, and further behind the pole when the pole occluded the top cylinder. (Although the mean judged cylinder positions were just behind the pole, four of the six observers judged the top cylinder to be in front of the pole when both cylinders occluded the pole and three of the six observers judged the top cylinder to be in front when the top cylinder occluded the pole and the bottom cylinder was occluded by the pole.) There was a small but consistent effect of whether the bottom cylinder was on the same side of the pole or on the opposite side. With the top cylinder behind the pole, it was judged slightly closer when the bottom cylinder was in front of the pole. With the top cylinder in front of the pole, it was judged further back when the bottom cylinder was behind the pole. This indicates some remaining effect of grouping the cylinders even when the interposition of the pole indicated that they were at different distances. Overall, these results confirm the expectation that occlusion limits the range within which motion parallax can affect judged distance.

GENERAL DISCUSSION

Overall, our results indicate that the judged position of an object in a 3-D scene is affected by the five variables manipulated in these experiments: The ground contact position, motion parallax, occlusion, the simulated distance between the occluded and occluding objects, and the presence of an additional object close to the occluding or occluded object. Previous studies of the effect of occlusion on perceived relative depth clearly indicate that occlusion, whether static or dynamic, is an effective source of information for depth order (e.g., Andersen & Braunstein, 1983; Braunstein et al., 1982). The present results show interactions between occlusion, motion parallax, and ground contact information that cannot be predicted from the separate effects of these variables and show quantitative effects of the presence of an occluding object on judged depth.

In stationary scenes (Experiment 1) we obtained judgements of the position of a cylinder occluding a pole that imply a reversal of the depth order expected from occlusion: The occluding object (cylinder) was judged further back in the scene than the occluded object (pole). Although the cylinder clearly appears to be in front of the pole when the two objects are compared directly, judgements of the cylinder position placed the cylinder further back than the pole in the scene. This result, and subjective reports of observers, suggest that observers do not necessarily take the relative distance of the cylinder and pole into account when judging the position of the cylinder in a static scene. This seems to be the case when ground contact information indicates that the cylinder is further back in the scene than the pole it occludes.

The pole did have some effect, however, as indicated by the greater distances judged in conditions in which the cylinder did not occlude the pole. When the cylinder was occluded by the pole, and the ground contact position was thus consistent with occlusion, the cylinder was judged further back in the scene. It was, however, judged closer than when the pole was absent. This result indicates that the insertion of an occluding object into a scene can have a quantitative effect on the perceived position of the occluded object, in addition to the expected ordinal effect. The most likely explanation for this quantitative effect in stationary scenes is that the equidistance tendency (Gogel, 1965) resulted in the cylinder appearing close to the pole, rather than simply behind the pole as would be required by occlusion.

In moving scenes (Experiment 2), the position of the cylinder and pole were ordered as expected from occlusion. A cylinder occluded by a pole was judged to be at a greater distance than the pole. A cylinder occluding a pole was judged to be closer than the pole and a cylinder occluded by a pole was judged to be further back in the scene than a cylinder by itself, indicating that the relative motion of the cylinder and pole reduced the tendency to perceive them as equidistant. An unexpected interaction was found between occlusion and motion parallax. When the cylinder was occluded by the pole, the judged position was influenced by motion parallax information. When the cylinder occluded the pole, however, there was no longer an effect of the difference in motion parallax information. Apparently with occlusion indicating a closer distance than that indicated by ground contact, motion parallax can support a depth order consistent with the occlusion information, but does not have a quantitative effect on judged distance.

A quantitative relation between occlusion and motion parallax was found with the scene in motion in Experiment 3. Variation in the pole position, which did not alter the depth order of the cylinder and the pole, altered the judged position of the cylinder when motion parallax indicated a cylinder position that was not consistent with the range of positions indicated by occlusion. Under these conditions, the judged position of the cylinder was within the range indicated by the ordinal information provided by occlusion, but the inconsistent information from motion parallax still had a quantitative effect in determining the judged position of the cylinder within that range.

The relationship of occlusion to ground contact, motion parallax, and the equidistance tendency can be described in terms of cue conflicts, but this is probably not the most useful analysis. It is more useful to consider the constraints underlying each source of information and the circumstances under which information in a scene is processed in accordance with these constraints. The constraint underlying information from occlusion is that an object that occludes another object is closer to the eye than the object that is occluded. (There are of course issues about when an object is treated perceptually as being occluded, but it is not necessary to go into this here because there is no ambiguity about the occlusion relationship in the present stimuli.) The present results and those of previous studies indicate that this constraint takes precedence over the other constraints to be discussed here: The visual system does not appear to relax this constraint. Some perceptions are inconsistent with occlusion, as in the case of the stationary displays with the cylinder in front of the pole in Experiment 1 and the tube attached to the rotating trapezoid (Kilpatrick, 1952), but these do not necessarily indicate that depth order is not determined by occlusion.

The constraint that objects do not float above the ground seems to be next in importance, but it can be violated in real scenes and is clearly subject to relaxation. An object stacked above other objects can be perceived as floating (Ni et al., 2005) and an object associated with an appropriate shadow (Kersten et al., 1997; Ni et al., 2004) is likely to be perceived as floating. The constraint that objects move rigidly with the scene appears to be even more readily relaxed, unless it is supported by additional grouping information, such as common motion of several objects, one of which is on the ground (Ni et al., 2005). Finally, there is the equidistance tendency (Gogel, 1965), which operates in the absence of other depth information, but still has an effect with other depth information present.

Overall, our results indicate that occlusion defines the range of positions in which an object is perceived in a scene, at least for scenes that are in motion. Within the range defined by occlusion, ground contact, and motion parallax determine the quantitative judged position. This occurs even when the scene positions specified by these other sources of information are not within the range defined by occlusion.

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