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Distance perception from motion parallax and ground contact

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Meng and Sedgwick (2001, 2002) found that the perceived distance of an object in a stationary scene was determined by the position at which it contacted the ground in the image, or by nested contact relations among intermediate surfaces. Three experiments investigated whether motion parallax would allow observers to determine the distance of a floating object without intermediate contact relations. The displays consisted of one or more computer-generated textured cylinders inserted into a motion picture or still image of an actual 3-D scene. In the motion displays, both the cylinders and the scene translated horizontally. Judged distance for a single cylinder floating above the ground was determined primarily by the location at which the object contacted the ground in the projected image (''optical contact''), but was altered in the direction indicated by motion parallax. When more than one cylinder was present and observers were asked to judge the distance of the top cylinder, judged distance moved closer to that indicated by motion parallax, almost matching that value with three cylinders. These results indicate that judged distance in a dynamic scene is affected both by optical contact and motion parallax, with motion parallax more effective when multiple objects are present.

The importance of the ground surface in specifying the layout of a 3-D scene was clearly described by Gibson (1947/1958, 1950). Gibson proposed that the perception of the visual world is not based on perceiving distances of objects from the eye across empty space but is based on perceiving relationships between objects and a background surface. The ground surface, he argued, was the most important background surface for distance perception because it is

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common to all terrestrial environments and is the surface that supports objects and the locomotion of most animals. Gibson (1946/1958) provided an analysis of the relevant information available in a retinal projection of a ground surface. Specifically, he described a set of retinal gradients that provide the slant of the ground surface and distance along the ground surface. For example, a retinal gradient of texture results from the change in projected texture density in the retinal image with increasing 3-D distance, a retinal gradient of size-of-similar objects results from the change in the projected extents of similar-size objects with increasing distance, and a retinal gradient of velocity (also referred to as motion parallax) results from the inverse relationship between the projected velocities of stationary objects and their distance from the observer, during movement of the observer.

A considerable body of literature now exists on retinal gradients and the perception of surface slant. (See Howard & Rogers, 2002, for a comprehensive review of depth perception research.) Until recently, however, only a few studies have directly addressed the role of the ground surface in the perception of layout in 3-D scenes (see, for example, Sedgwick, 1983, 1987; Sedgwick & Levy, 1985; for a recent review, see Sedgwick, 2001). Some studies have considered judged distance along the ground in outdoor scenes (Levin & Haber, 1993; Toye, 1986). Loomis (e.g., Loomis, da Silva, Fujita, & Fukusima, 1992; Loomis, da Silva, Philbeck, & Fukusima, 1996; Loomis, Philbeck, & Zahorik, 2002) has examined the perception of distance, location, and shape along a ground surface in outdoor scenes, using both open-loop walking and perceptual judgements. In the open-loop walking tasks, observers viewed a target and then attempted to walk blindfolded to the location of the target, attempted to point to the target while walking along a perpendicular path, or attempted to walk towards the target after walking along an oblique path. In the perceptual judgement tasks, observers constructed depth intervals on the ground to match frontal-parallel intervals. These studies involved the perception of where objects contacted the ground, as well as information for distance from the observer to points along the ground surface.

Effects of characteristics of the ground surface on judged distance were studied by Sinai, Ooi, and He (1998). Using both a blindfolded walking task in which observers turned 90° and attempted to walk a distance equivalent to the perceived egocentric distance of a target and a perceptual judgement task in which observers turned 90° and set the distance of an object to match the perceived distance of the target, they found that a change in texture (from grass to concrete) across the distance being judged resulted in an underestimation of the distance, but a gap in the texture resulted in an overestimation. Feria, Braunstein, and Andersen (2003) replicated the effect of a change in texture on judged distance, finding that judged distance is reduced in the presence of any texture discontinuity, whether produced by a change in texture patterns, a contrast reversal of the same pattern, or a misalignment of identical regular textures, either along a ground surface in a 3-D scene or in a frontal plane.

Gibson (1950, p. 178) pointed out that the perceived position of an object along a ground surface is determined by the position at which the object contacts the ground in the optical projection—the ‘‘optical contact’’ position—in the absence of relative motion or stereoscopic depth. He demonstrated the effect of optical contact with a photograph (p. 179) in which the object that appeared more distant was physically closer in the scene, but was suspended above the ground by an unseen support (see also Sedgwick, 1983, 1989). More recently, Meng and Sedgwick (2001, 2002) examined the role of mediated ground contact in determining the perceived positions of objects in a stationary scene. They placed an object on a platform that was either resting on the ground or floating above the ground. The optical contact position of the floating platform was more distant from the observer than the simulated distance of the platform. Observers moved a marker along a track extended in depth in the scene to indicate the perceived position of the object. The judged location of an object on a platform depended on where the object contacted the platform in the image and on where the platform contacted the ground in the image. They referred to this combined effect as a nested contact relation.

Information about optical contact can be expected to combine with other information about the relative distances of objects in determining perceived layout. Cutting and Vishton (1995) presented an analysis of the information available from different sources, for different distances from an observer. Some of these sources, such as motion parallax, provide quantitative information about layout; other sources, such as occlusion, provide qualitative information. Although both optical contact and motion parallax provide quantitative information about layout, the use of these cues in judging relative depth relies on very different constraints. Optical contact specifies layout under a constraint that objects do not float above the ground. Motion parallax specifies layout in depth under a constraint of rigid motion, that is, no relative motion between the objects and the ground or among the objects. Both of these constraints can be violated, of course. Some objects do float above the ground. Objects and surfaces may move independently of each other.

In the present series of experiments we examined the interaction between optical contact information and motion parallax in specifying layout in a 3-D scene. If optical contact specifies a distance that is different from the simulated distance of an object (as when the object is floating above the ground), will the addition of motion parallax result in a perception of the object at its simulated distance? In a single image of a stationary scene, it is not possible to distinguish a floating object from an object on the ground unless additional information is provided. We can think of motion parallax as providing additional information that disambiguates the information provided by optical contact. But there is another interpretation of the situation: Both optical contact and motion parallax, like all depth cues, provide ambiguous information. With optical contact and motion parallax providing different indications of an object's position in the scene, the object may be perceived as lying on the ground and sliding back and forth relative to the scene (an optical contact interpretation) or as floating above the scene and moving rigidly with the scene (a motion parallax interpretation). Which interpretation is accepted by an observer may be a reflection of which underlying constraint can be relaxed or ignored, in this case, a gravity-based constraint for optical contact and a rigid motion constraint for motion parallax.

In the first experiment the optical contact position of the object was varied while the simulated distance, indicated by motion parallax, was held constant. In the second experiment, in contrast, the optical contact position was held constant while the simulated distance was varied. The third experiment examined the effect of the number of cylinders that were stacked above the ground, both for stationary scenes and for scenes shown in motion.

Although most research on the perception of 3-D objects in 3-D scenes has used either computer-generated scenes or directly observed real-world scenes, both of these methods have limitations (Sauer, Braunstein, Andersen, & Bian, 2001). Simulated scenes provide good control over stimulus characteristics but may lack the abundance of information sources available in natural environments. Real-world scenes provide this abundance of information but it is difficult to control all attributes of objects in such scenes. In the present research, we balance these two methods by adding computer-generated objects (textured cylinders and a track with a marker) to a movie of a real scene.

EXPERIMENT 1: VARIATIONS IN OPTICAL CONTACT WITH CONSTANT MOTION PARALLAX

The purpose of Experiment 1 was to investigate the effect of motion parallax information on perceived distance in the presence of optical contact information. While the distance of the object simulated by motion parallax and the simulated height of the top surface above the ground were kept constant, the optical contact position was varied by varying the vertical extent of the object, and thus the separation of the bottom of the object from the ground. This was analogous to the variation in platform heights in Meng and Sedgwick's (2001) first experiment. If the motion parallax information was sufficient to determine judged distance, a constant distance should be perceived regardless of the variations in the optical contact location.

Method

Observers. The observers were 14 students from the University of California. All observers 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.

Apparatus. A Pentium 4 2 GHz computer displayed the stimuli on a 21 inch (53 cm) Dell monitor, with a resolution of 1024 (horizontal) × 768 (vertical) and a refresh rate of 85 Hz. The experiment was carried out in a darkened room. Observers viewed the displays binocularly through a 19 cm diameter collimating lens with a focal length of 75 cm, with their heads stabilized by a chin- and headrest. The distance between the observer and the display screen was 85 cm. 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 assure that the observer would not see the location of the monitor. Responses were made using a Microsoft SideWinder joystick.

Stimuli. The displays consisted of computer-generated cylinders and a computer-generated track with a red marker, superimposed on a background movie of an actual 3-D scene. The background movie consisted of 50 photographs taken with a Kodak DC260 digital camera with a 35 mm equivalent lens. The photographs were taken at fixed positions along a horizontal track that were spaced 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 photographs were cropped from the original size of 1536 × 1024 pixels to 1024 × 768 pixels, with the original pixel aspect ratio kept unchanged. An example of a cropped photograph with a cylinder, track, and marker superimposed is shown in Figure 1.

In the 3-D simulation, the cylinder was located either 13 m (front position) or 19 m (back position) from the observer. To keep the projected sizes of the cylinders the same at these two positions, the simulated cylinder diameters were set at 36 cm and 52 cm in the front and back positions, respectively. The height (vertical dimension) of the cylinder was 9 cm, 27 cm, or 45 cm (designated as short, medium, and tall) in the front position and 13 cm, 39 cm, or 65 cm in the back position. Figure 2 shows the three cylinder heights with the cylinder located at the front position. The top surface of the cylinder was kept at a constant height above the ground at each position. For the tall cylinder (Figure 2a), the relative velocities of the cylinder and scene were consistent with a cylinder resting on the ground and translating rigidly with the scene. For the short and medium cylinders (Figures 2b and 2c), the relative speeds of the cylinder and the ground surface were consistent with one of two possibilities: (1) The object was floating above the ground but moving rigidly with the ground, or (2) the object was located on the ground but was moving relative to the ground (i.e., sliding across the ground). The displays were also consistent with intermediate possibilities combining floating and nonrigidity.

Figure 1. A frame from the stimulus display showing a cylinder in the back position and the track with the adjustable red marker.

Design. The independent variables were the height of the cylinder (tall, medium, and short) and the simulated position of the cylinder in the scene (front and back). Each observer responded to 10 replications of each of the six conditions. The 60 trials were presented in a different random order for each observer in two blocks of 30 trials, preceded by a practice block that was the same as the first block of trials.

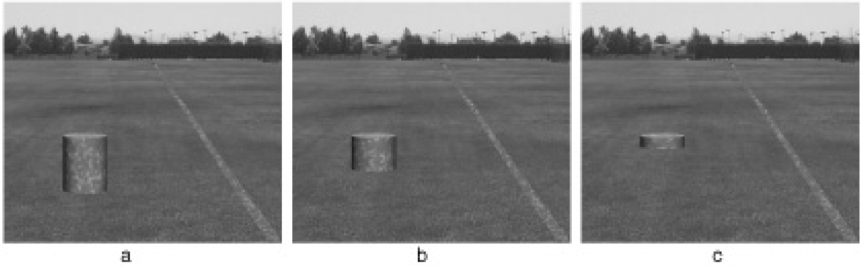

Figure 2. Cylinders in the front position: (a) Tall, (b) medium, and (c) short. (The displays showed the full scene as illustrated in Figure 1.)

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 cylinder. This was similar to the task used by Meng and Sedgwick (2001, 2002). The marker was adjusted with a joystick and the observers pressed the trigger button on the joystick when they were satisfied with their response.

Results and discussion

Figure 3 shows judged distance as a function of cylinder height for the two scene positions, averaged across the 14 observers. For 12 of the 14 observers, judged distance increased with decreasing cylinder height (that is, increased with increasing space between the cylinder and the ground plane in the 3-D simulation) at both scene positions. A three (cylinder height) by two (scene position) repeated measures ANOVA showed significant main effects for projected height of the cylinder, $F(2, 26) = 18.17$, $p < .01$, and scene position, $F(1, 13) = 220.70$, $p < .01$, and a significant interaction, $F(2, 26) = 10.11$, $p < .01$.

If the perceived distance was determined only by the optical contact location, the results should match the dashed lines in Figure 3. If, on the other hand, the results were consistent with the motion parallax information (under an assumption of rigid motion of the cylinder with the ground surface), the cylinder

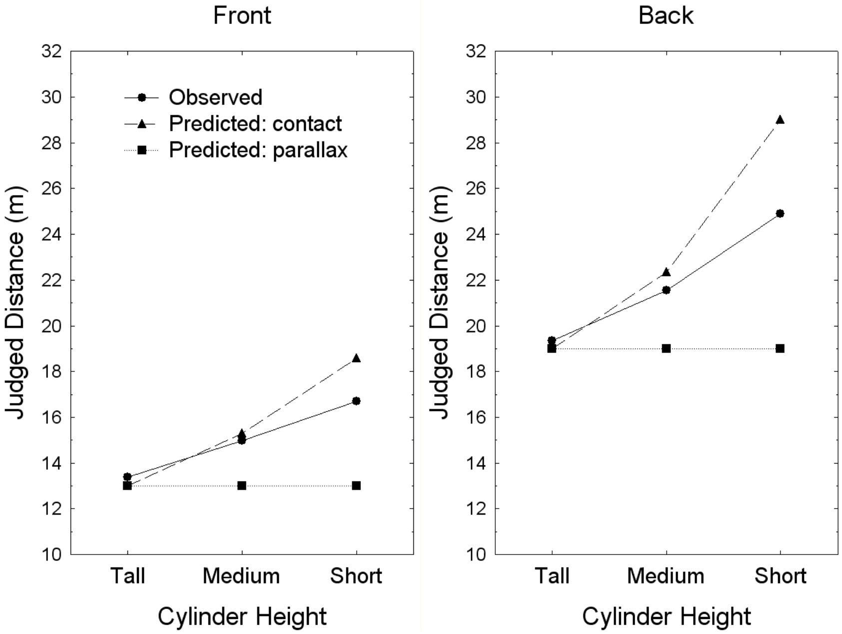

Figure 3. Judged distance as a function of cylinder height for two scene positions in Experiment 1.

should be perceived at a constant distance, regardless of its height. This is indicated by the dotted lines in Figure 3. The results indicate that motion parallax altered the judged position of the object in the scene relative to that predicted from optical contact, but that the judged position was closer to the optical contact position than to the position indicated by rigid motion. In other words, there appears to have been a compromise between these two sources of information, with greater weight given to optical contact.

Control experiment. Both stationary and motion versions of each of the displays, except those with the middle cylinder height, were included in a control experiment with 10 naive observers, using the same procedure. Results for the motion conditions were similar to those in the main experiment. In the stationary conditions the cylinder position was judged according to its optical contact position, as would be expected from Meng and Sedgwick's (2001) results.

EXPERIMENT 2: VARIATIONS IN MOTION PARALLAX WITH CONSTANT OPTICAL CONTACT

In Experiment 1, motion parallax indicated a constant cylinder position as the optical contact position was varied across trials by varying the distance of the cylinder above the ground. The motion of the cylinder was thus constant at each of the two scene positions. If motion parallax affects the perceived position of the cylinder, as indicated in Experiment 1, then variations in cylinder speed corresponding to variations in distance from the observer should result in variations in judged distance. The manipulations in Experiment 2 were complementary to those in Experiment 1 in that we varied the cylinder position indicated by motion parallax across trials, while keeping the optical contact position constant at one of two levels. The cylinder's projected size and height in the image was kept constant across all conditions. This was done by varying the cylinder's simulated height and distance above the ground, as shown in Figure 4.

Method

Observers. The observers were 16 students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity, and all were naive about the purpose of the experiment. None had participated in Experiment 1. The observers received extra credit for participating.

Apparatus and procedure. The apparatus and procedure were the same as in Experiment 1.

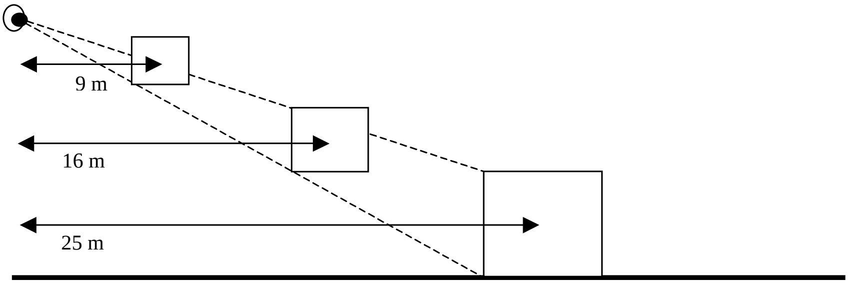

Figure 4. The three simulated cylinder positions in the front of the scene. The cylinders were adjusted in size to project the same image. The distances in the back of the scene were 16 m, 25 m, and 34 m, with corresponding adjustments in the sizes.

Stimuli. The background scene was the same as in Experiment 1. All cylinders were the same projected height as the short cylinder in Experiment 1. The projected cylinder was given one of two optical contact positions, 25 m or 34 m from the observer in the simulated scene. At each of these two image positions the cylinder was assigned a translation velocity corresponding to one of three simulated distances. At the 25 m optical contact position, the distances simulated by motion parallax were 7 m, 16 m, and 25 m. The 7 m and 16 m motion parallax conditions thus represented cylinders floating above the ground, whereas the 25 m motion parallax condition represented a cylinder lying on the ground. Similarly, at the 34 m optical contact position, the distances simulated by motion parallax were 16 m, 25 m, and 34 m, with the first two conditions representing floating cylinders and the third representing a cylinder lying on the ground.

Design. The independent variables were the optical contact position (25 m or 34 m) and the distance simulated by motion parallax (7 m, 16 m, and 25 m or 16 m, 25 m, and 34 m). Each observer responded to 10 repetitions of each of the six conditions. The 60 trials for each observer were randomly arranged in two blocks, preceded by a practice block of 30 trials.

Results and discussion

Judged cylinder position as a function of projected scene position and motion parallax, averaged across the 16 observers, is shown in Figure 5. A three (simulated distance) by two (optical contact position) repeated measures ANOVA showed significant main effects for simulated distance, $F(2, 30) = 11.25$, $p < .01$ and optical contact position, $F(1, 15) = 91.16$, $p < .01$. The interaction was not significant, $F(2, 30) = 2.83$, $p > .05$. If the perceived distance was determined only by optical contact, a constant distance should have been

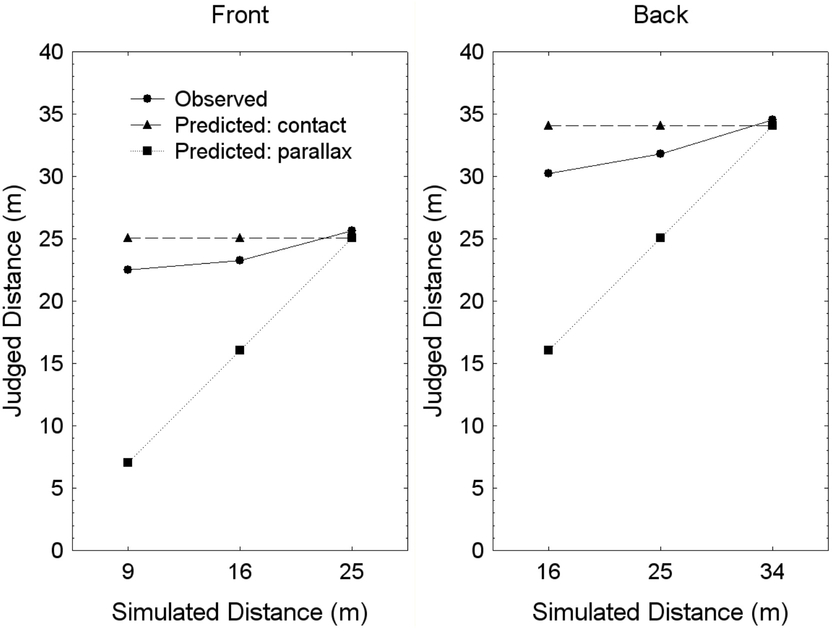

Figure 5. Judged distance as a function of simulated distance for two scene positions in Experiment 2.

judged for each of the two optical contact positions, as shown by the dashed lines. If, on the other hand, the results were consistent with the motion parallax information (under an assumption of rigid motion), the cylinders should be perceived at different distances, as indicated by the dotted lines. The results indicate that motion parallax altered the judged position of the object in the scene relative to that predicted from optical contact, but as in Experiment 1 the judged position was closer to that indicated by optical contact than to the position indicated by motion parallax. There appears to again have been a compromise between these two sources of information, with greater weight given to the optical contact information.

Control experiment. A control experiment, similar to the Experiment 1 control experiment, was conducted with 10 naive observers. Both stationary and motion versions of each of the displays, except for the intermediate positions simulated by motion parallax, were included. (This was relevant only for the motion stimuli.) Results for the motion conditions were similar to those in the main experiment, whereas in the stationary conditions the cylinder position was judged according to its optical contact position.

EXPERIMENT 3: EFFECTS OF MULTIPLE OBJECTS

In Experiments 1 and 2 there was a clear effect of motion parallax, but judged distance was determined primarily by optical contact. This may have occurred because the effectiveness of motion parallax is limited when only one object and a ground surface are displayed in motion. This is because the perception of an object moving relative to a surface is a reasonable alternative to the perception of an object moving rigidly with the surface, and appears to be preferred to a perception of an object floating above a surface. If two objects were present, however, perceiving the objects' positions according to optical contact would require perceiving the two objects and the surface each moving at a different speed. These three speeds would coincide exactly with the projected speeds that would be produced by a surface and two objects located at the same distance from the observer, all moving rigidly. With three objects, the perception of the objects moving at different speeds should be even less likely. Adding additional objects could have effects unrelated to motion, however. The objects might be grouped and thus perceived as being at the same location in the scene, that is, stacked one above the other, rather than at varying locations. For this reason we examined both motion parallax scenes and stationary scenes containing one, two or three cylinders.

Observers. The observers were 20 students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity and were naive about the purpose of the experiment. None had participated in Experiments 1 or 2. The observers received extra credit for participating in the experiment.

Apparatus and procedure. The apparatus was the same as in Experiments 1 and 2. The procedure was the same as in Experiments 1 and 2, except that the observers' task was to judge the distance of the top cylinder, if there was more than one.

Stimuli. The background scene was the same as in Experiments 1 and 2. One, two, or three cylinders were superimposed on the scene (Figure 6). The projected size of each cylinder was the same as that of the short cylinder in Experiment 1. In the motion parallax simulation with three cylinders, the bottom cylinder was resting on the ground at 13 m or 19 m and the other two cylinders were stacked above the bottom cylinder, with simulated vertical separations of 9 cm in the near position and 13 cm in the far position. For the two-cylinder conditions only the top two were displayed and for the one-cylinder conditions only the top cylinder was displayed. The optical contact position of the top cylinder was 25 m or 34 m, regardless of the number of cylinders displayed. The scene and the cylinders were either translating horizontally or stationary.

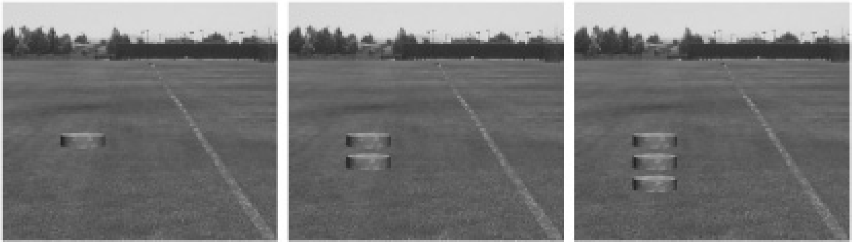

Figure 6. Cylinder arrangements in Experiment 3. (The displays showed the full scene as illustrated in Figure 1.)

Design. There were three independent variables, the number of cylinders (1, 2, or 3), the simulated position of the cylinders (13 m or 19 m), and whether the scene was in motion or stationary. The first two variables were run within observers; the third variable was run between observers. Each observer responded to 10 repetitions of each of the six within-observer conditions. The 60 trials were divided into three blocks based on number of cylinders, with half of the observers receiving the blocks in the order 1-2-3 and half receiving the blocks in the order 3-2-1. The stimuli in each block were presented in a random order. The three experimental blocks were preceded by a practice block with the same number of cylinders as the first experimental block.

Results and discussion

Judged distance, as a function of number of cylinders, scene position, and motion, averaged across observers, is shown in Figure 7. The dashed line indicates the optical contact position of the top cylinder (or of the cylinder, if there was only one) and the dotted line indicates the position simulated by motion parallax. Both of these positions were constant across number of cylinders. A three-way ANOVA with two within-observers variables and one between-observers variable showed significant main effects for scene position, $F(1, 18) = 377.49$, $p < .01$, for number of cylinders, $F(2, 36) = 8.04$, $p < .01$ and for motion vs. stationary, $F(1, 18) = 24.33$, $p < .01$. As can be seen in Figure 7, the cylinder was judged as closer in each of the motion conditions than in the corresponding stationary condition, but judged distance decreased with an increase in the number of cylinders in both the stationary and the motion displays. This indicates that the effect of increasing the number of cylinders was not entirely due to motion, but may be related to grouping of the cylinders, leading to a perception of the cylinders as stacked on top of one another rather than located at different positions in depth. The effects in the stationary case are analogous to the nested contact effects reported by Meng and Sedgwick (2001, 2002) except that in the present case the objects were not in direct contact but

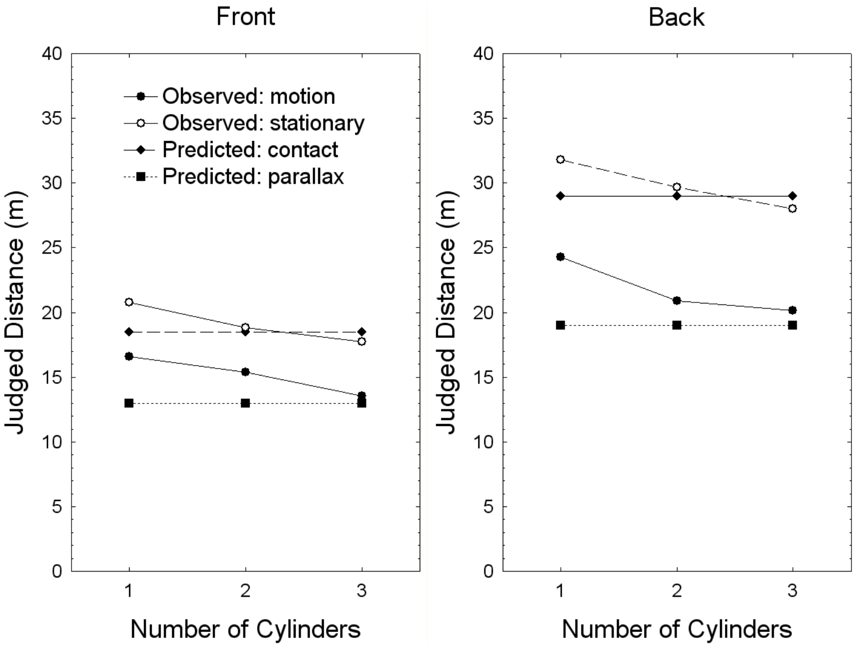

Figure 7. Judged distance as a function of number of cylinders for moving and stationary displays at two scene positions in Experiment 3.

may have been related to one another across vertical gaps. It is especially important to note that with three cylinders in motion, judged distance is very close to the distance simulated through motion parallax, demonstrating that under these particular conditions optical contact information is no longer dominant in determining judged distance.

Control studies

It is possible that the tendency to judge the distance of the top cylinder according to the optical contact position of the bottom cylinder was due to the vertical alignment of the cylinders in the 3-D simulation, rather than to their rigid motion, when more than one cylinder was present in the scene. We conducted two control experiments to examine this possibility.

Nonrigid horizontal motion. The displays were similar to the motion displays in Experiment 3, except that the cylinder speeds were altered so that the speed of each cylinder corresponded to its optical contact position. 10 naive observed participated. With this change in the cylinder speeds, the number of cylinders did not have a significant effect on judged distance.

Rigid motion without alignment. The displays were again similar to the motion displays in Experiment 3, except that the cylinders were not aligned vertically. The top cylinder was positioned to the left of the bottom cylinder's position by 27 cm in the front position and 39 cm in the back position, in the simulated 3-D scene. The middle cylinder was positioned to the left of the bottom cylinder's position by 9 cm in the front position and 13 cm in the back position. (As in the main experiment, some displays contained only the top cylinder, others the top and middle cylinders, and others all three cylinders.) The cylinders moved rigidly in accordance with their scene positions, as in the main experiment. Ten naive observers participated. The effect of number of cylinders was significant, although smaller than that found in Experiment 3. In combination, these two control experiments indicate that vertical alignment of the cylinders is neither necessary nor sufficient to account for the results of Experiment 3.

GENERAL DISCUSSION

Motion parallax clearly interacts with optical contact information in determining the perceived position of an object in a 3-D scene. With a single object moving rigidly with the ground plane, perceived location is determined primarily by optical contact but is altered when motion parallax indicates that the object is not in contact with the ground in the 3-D scene. Even when the optical contact location of an object is kept constant, varying the speed with which the object translates changes the judged distance. With two objects moving rigidly with the ground plane, judged object location was determined primarily by motion parallax. With three objects, judged location was almost equal to that indicated by motion parallax.

The effects found with multiple objects appear to have at least two components, one present in both stationary and motion parallax scenes and one specific to motion. The stationary displays of two or three cylinders could be interpreted as cylinders lying on the ground at different distances or stacked vertically at the same distance. In the first case the top cylinder would be perceived at its optical contact position. In the second case the top cylinder would be perceived at the optical contact position of the lowest cylinder. Our results indicate a tendency to perceive multiple cylinders as forming a vertical stack, rather than as each lying on the ground, with the judged distance of the top cylinder falling between its optical contact position and the optical contact position of the lowest cylinder. The cylinders are apparently grouped together, but grouping alone does not imply that they would be perceived as stacked vertically. The perception of the cylinders as stacked vertically is consistent with the equidistance tendency (Gogel, 1965), and that tendency may explain this perception.

With the addition of motion, the judged distance of the top cylinder moves still further from its optical contact position and closer to its simulated position.

This could be due to a tendency to perceive a group of objects that have projected motions compatible with rigid motion in 3-D as moving rigidly in 3-D (Ullman, 1979). If a rigidity constraint underlies the effect of number of cylinders, however, one might expect judgements to change more rapidly with an increase in the number of cylinders for the motion condition than for the stationary condition, but the slope of these two curves is about the same. Although rigidity cannot be ruled out, another explanation of the effect of motion may be that the common horizontal motion of the cylinders in 3-D enhanced the perception of the cylinders as forming a group, and thus enhanced the perception of the distance of the top cylinder being the same as that of the bottom cylinder. We have made informal observations with displays in which three cylinders were translating horizontally but were given additional, independent vertical motions. The perceived distance of the top cylinder was no different for these cylinders, which displayed nonrigid motion, than for the cylinders that moved rigidly. This suggests that it is the equal 3-D translation speed (the Gestalt principle of common fate), and not rigid motion per se, that is responsible for the effect of common horizontal motion of a group of cylinders on perceived distance.

The results of the two control experiments related to Experiment 3 suggest that the perception of multiple cylinders as located at the same position in the scene in motion parallax displays is based on common motion in 3-D and not vertical alignment of the edges of the cylinders. In the first control experiment the amplitude of the horizontal motions of the upper cylinders was altered to match their optical contact positions. With the horizontal motions no longer consistent with rigid motion or a common horizontal translation, the upper cylinders were judged as resting on the ground rather than stacked above the lower cylinder. In the second control study the cylinders were shifted horizontally in the simulated scene so they were no longer aligned vertically. This reduced but did not eliminate the tendency to judge the upper cylinders as moving rigidly with the lower cylinder. It might be expected that with further separation between the cylinders, either horizontally or vertically, the effect of multiple cylinders on perceived distance would diminish and eventually disappear.

A possible explanation for the dominance of the optical contact information in determining the perceived position of the cylinder in Experiments 1 and 2, and of the single cylinder in Experiment 3, is that the response would match the optical contact position if the observer merely aligned the marker and the cylinder horizontally in the image. We have several reasons for discounting this possibility. First, it would mean that the observers were not following instructions to respond according to a 3-D perception. Of course this is possible, but the systematic deviations from the optical contact response when motion parallax or stacking of the cylinders provided conflicting 3-D information suggests that the observers were responding to 3-D relationships and not directly to height in the image. Meng and Sedgwick's (2001, 2002) results provide further evidence that observers making similar judgements were not merely aligning the marker with the object in the image. They observed variability across different conditions that would not be expected if observers had just aligned the marker and the object horizontally in the image.

The interaction of optical contact and motion parallax in determining the judged distance of an object in a 3-D scene may be regarded as an instance of cue combination. Our data does not distinguish between models in which depth is calculated separately for each cue and a weighted average determines judged depth, and models in which information from the two sources is combined to compute a single depth estimate. We examined the distributions of responses on individual trials for conditions that suggest a compromise between the distance indicated by optical contact and the distance indicated by motion parallax. These distributions are unimodal, suggesting that the compromise occurs on individual trials and not through averaging of trials in which the responses are based on one cue or the other.

On the assumption that judged depth can be modelled as a weighted function of the distance indicated by optical contact and the distance indicated by motion parallax, we calculated the weights that best fit our data. In Experiment 1 and Experiment 2 the equation used to fit the judgement results was judgement = w_{motion} * simulated position + $w_{optical}$ * optical contact position, where $w_{optical} = 1 - w_{motion}$. The value assigned to w_{motion} for Experiment 1 and Experiment 2 was .20, using a least squares difference criterion for determining the best fit. The estimated judgements and the observed judgements for Experiments 1 and 2 are shown in Figures 8 and 9. The model accounted for 98.5% of the variance in the 12 data points in the two figures.

Two additional variables had to be considered in applying a weighted combination model to Experiment 3: The number of cylinders and whether the scene was stationary or moving. In the stationary conditions we used a weighted combination of the optical contact position of the cylinder being judged and the optical contact position of the lowest cylinder in the stack. With one cylinder present, these were of course the same. With three cylinders present the optical contact position of the lowest cylinder was the same as the simulated (physical) position in the scene of the top cylinder. With two cylinders present, the optical contact position of the lowest cylinder was intermediate between the optical contact position of the top cylinder and the simulated position of the top cylinder. We used the equation judgement = $w_{optical}$ * optical contact + w_{lowest} * lowest contact, where lowest contact is the optical contact position of the lowest cylinder and $w_{lowest} = 1 - w_{optical}$. The value used for $w_{optical}$ was .94. In the motion case we used the simulated (motion parallax) position of the top cylinder and the optical contact position of the lowest cylinder. This was based on the assumption that when multiple cylinders are present, and these cylinders have a common motion, it is the optical contact position of the lowest cylinder, not that

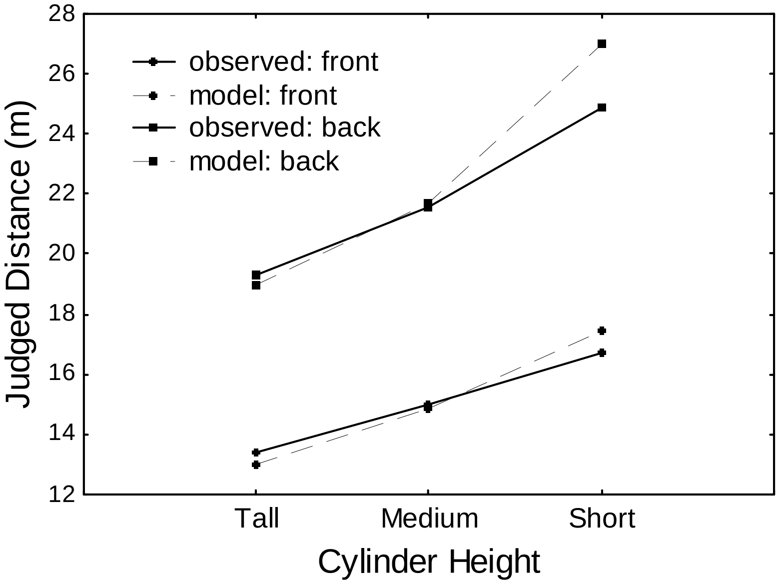

Figure 8. Comparison of model estimates to observed data in Experiment 1.

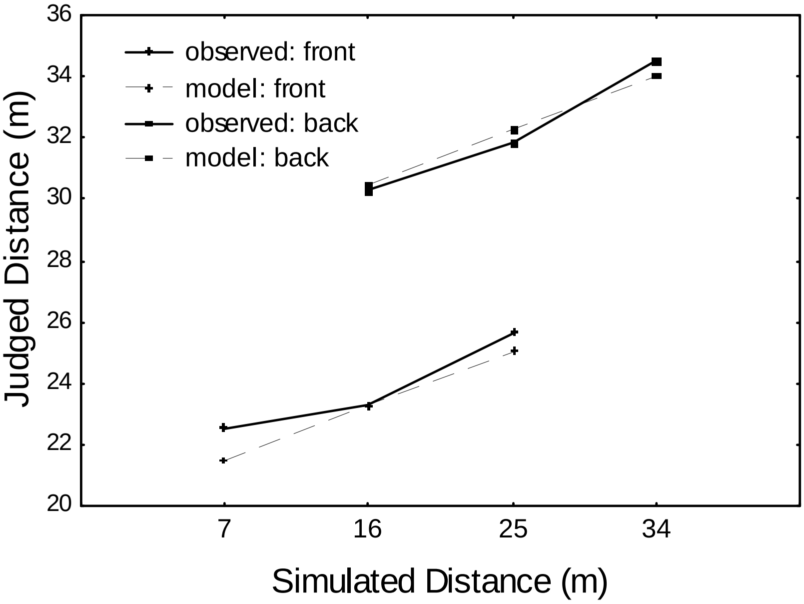

Figure 9. Comparison of model estimates to observed data in Experiment 2.

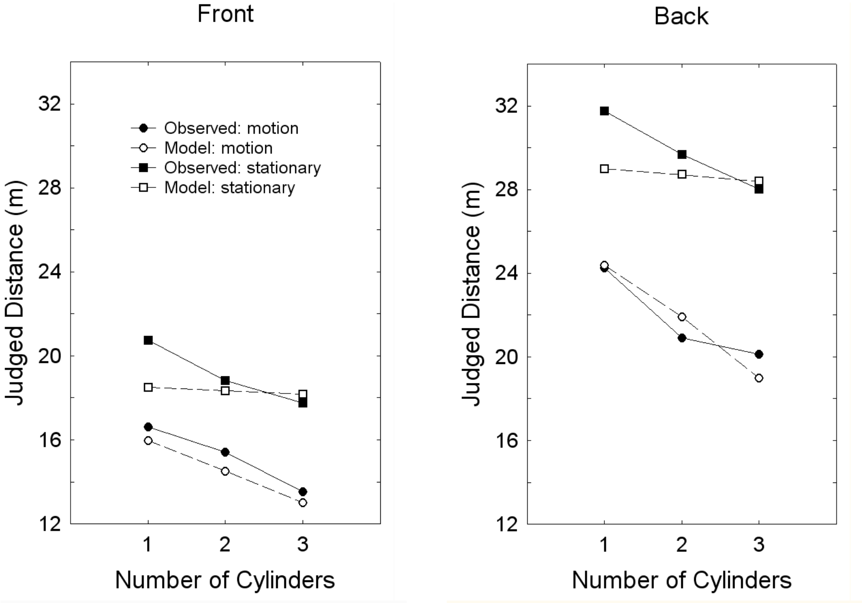

Figure 10. Comparison of model estimates to observed data in Experiment 3.

of the top cylinder, that affects the judged position of the top cylinder. The equation used was judgement = w_{motion} * simulated position + w_{lowest} * lowest contact. The value used for w_{motion} was .46. The estimated and observed judgements are compared in Figure 10. The model accounted for 95.3% of the variance in the stationary data and 97.6% of the variance in the motion data. The error in the predictions cannot be reduced for the stationary condition for one or two cylinders, without adding a constant to the prediction equation, because the judged values do not fall between the two values used in the prediction. Although these simple weighting functions generally fit the observed data, at least for the motion conditions, this does not rule out alternative possibilities for accounting for the results. The model estimates are presented only to show that the results are generally consistent with a compromise solution based on a weighted function of two variables in each experiment.

The present results provide further support for Gibson's (1946/1958, 1950) theoretical position that the perception of the distances of objects in a 3-D scene depends on how these objects are related to the ground surface. In addition, our results provide indirect support for Meng and Sedgwick's (2001, 2002) conclusion that ground contact relations can be mediated through intermediate surfaces. With more than one cylinder in a scene, whether the scene was stationary or moving, the judged position of the top cylinder appears to have been influenced by the optical contact position of the lowest cylinder, although the cylinders were not in contact with each other in the projection or in the simulated scene. This suggests that nested contact relations may propagate across gaps between objects, especially when the objects are grouped perceptually. In the present case, common 3-D motion of the cylinders appears to have been especially effective in enhancing this grouping.

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