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Discriminating direction of motion trajectories from angular speed and background information

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Abstract The effects of a background scene on the perception of the trajectory of an approaching object and its relation to changes in angular speed and angular size were examined in five experiments. Observers judged the direction (upward or downward) of two sequentially presented motion trajectories simulating a sphere traveling toward the observer at a constant 3-D speed from a fixed distance. In Experiments 1–4, we examined the effects of changes in angular speed and the presence of a scene background, with changes in angular size based either on the trajectories being discriminated or on an intermediate trajectory. In Experiment 5, we examined the effects of changes in angular speed and scene background, with angular size either constant or consistent with an intermediate 3-D trajectory. Overall, we found that (1) observers were able to judge the direction of object motion trajectories from angular speed changes; (2) observers were more accurate with a 3-D scene background, as compared with a uniform background, suggesting that scene information is important for recovering object motion trajectories; and (3) observers were more accurate in judging motion trajectories based on angular speed when the angular size function was consistent with motion in depth than when the angular size was constant.

Keywords Motion in depth · Scene Perception

An important goal of vision is to recover the motion of objects in the environment and to use that information to guide behavior. For instance, a driver needs to constantly monitor the motion trajectories of other vehicles and pedestrians in order to detect and avoid potential collisions. Failure to correctly determine trajectory information may result in serious consequences for the safety and health of drivers and pedestrians. In general, three types of information can be used to recover object motion in 3-D scenes: (1) change in the angular speed and angular size of an object's projected image, (2) binocular information based on the rates of change in disparity and vergence, and (3) scene information that can be used to determine depth and layout of objects in a scene and how this changes during object motion. In the present study, we examined the use of change in angular speed and scene information for determining the trajectory of moving objects.

As an object travels in 3-D space, both the angular speed and angular size of its projection vary according to the speed and direction of its motion and its distance to the observer. Previous research on object motion has focused primarily on the use of this optical information in perceiving motion trajectories (e.g., Duke & Rushton, 2012; Harris & Drga, 2005; Portfors-Yeomans & Regan, 1997; Regan & Gray, 2000; Regan & Kaushal, 1994; Rushton & Duke, 2007; Todd, 1981). For instance, Todd provided a mathematical model demonstrating that visual information from optic flow could be used to determine different characteristics of a motion trajectory, such as a moving object's angle of approach, time to passage, and whether it will land in front of or behind the point of observation. Regan and Kaushal proposed that the direction of an object moving in depth could be specified by the translational angular velocity and the rate of expansion of its image. They showed that observers could detect the direction of motion in depth with a high degree of accuracy. Harris and Drga found that observers used estimates of visual direction to determine the direction of object motion in 3-D for small trajectory angles at near distances.

In addition to the effects of changes of angular speed and angular size, studies have found that the perception of object

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motion trajectories is affected by the optic flow information of the background scene induced by self-motion (Brenner & van den Berg, 1996; Matsumiya & Ando, 2009; Rushton & Warren, 2005; Warren & Rushton, 2009). For instance, Warren and Rushton examined how observers determine object motion from simulated self-motion ("optic flow parsing") with either binocular disparity or monocular depth cues (motion parallax, relative size, linear perspective, and occlusion) presented. They found that performance improved with the availability of depth cues and concluded that monocular and binocular depth cues are important for parsing object and observer motion. In addition, Rushton and Duke (2009) showed that observers could estimate the speed of an approaching object more accurately with the object moving against a background scene, as compared with a dark room.

In the present study, we examined the effect of a 3-D scene background on the perception of the trajectory of an object moving in depth when angular speed and size information is available. Three-dimensional backgrounds can be defined by binocular information (stereopsis), monocular depth cues (e.g., perspective, texture gradient, occlusion, etc.), or both. In the present study, we were interested in background scenes defined by monocular depth cues. As an object moves against a 3-D background, the angle of approach ϕ of the moving object can be recovered from scene information by

$$\tan\phi = (-\dot{d} + d x')/(\dot{d} x' + d),$$

where x' is the projected position of the object, d is the absolute distance to the moving object, and $\dot{d}$ is the time derivative of d. Absolute distance d can be determined from one of two alternative calculations using either eye height and angle of declination or a combination of eye height and texture gradient. The distance of an object in a scene could be specified as

$$d = H/\tan(\eta),$$

where d is the absolute distance, H is the eyeheight of the observer, and η is the angle of declination of an object on the ground (Ooi, Wu, & He, 2001; see also Sedgwick, 1986). Alternatively, absolute distance along a textured ground surface can be specified as

$$d = H \times (\cos\alpha_1/\sin\alpha_2) \times \tan(\beta_1/\beta_2),$$

where H is the eyeheight of the observer, α_1 and α_2 are the projected angles from the observer to two texture elements on the ground surface, and β_1 and β_2 are the projected extents of the texture elements (i.e., $\tan(\beta_1/\beta_2)$ is the texture gradient of the surface).

The importance of a background scene, especially the ground surface, on the perception of 3-D space was discussed as early as 1,000 years ago in Alhazen's (1989) writings. Gibson (1950) emphasized the unique role of the ground surface in organizing the visual environment by proposing that the ground surface served as a common reference frame from which both egocentric and exocentric distances of objects in a scene are determined. Background surfaces, especially the ground surface, provide layout information in a scene. Previous studies have found that many visual tasks were performed in accordance with such information. These tasks include visual search (He & Nakayama, 1992), texture segregation (He & Nakayama, 1994), perception of subjective contours (Gilliam & Nakayama, 2002), and change detection (Bian & Andersen, 2010). Disruption of a continuous texture on a ground plane results in decreased perceived distance of objects in a scene (Feria, Braunstein & Andersen, 2003; Sinai, Ooi, & He, 1998). Given the importance of background scenes, especially the ground surface, on the perception of 3-D space, it is possible that the distance information of objects in a scene is used in combination with the change in angular speed and angular size to judge the trajectories of moving objects.

Recently, Zhang, Braunstein, and Andersen (2013) found that judgments of the magnitude and sign of the curvature for trajectories at eye level were based primarily on changes in angular size. In the present study, observers were asked to discriminate between upward and downward trajectories and curved and linear trajectories presented below eye level. For these trajectories, the angular size functions are almost identical for upward versus downward and straight versus curved conditions. This allowed us to examine the effects of angular speed for discriminations that cannot be made accurately on the basis of angular size. Specifically, we examined (1) whether observers can discriminate object motion trajectories on the basis of angular speed and (2) how background scene information was combined with changes in angular speed in recovering object motion trajectories.

For many cases of object motion, the 3-D direction of motion (leftward or rightward, upward or downward) will be correlated with the projected motion direction. For example, upward motion in depth will usually contain upward-projected velocity, whereas downward motion in depth will usually contain downward-projected velocity. This situation makes it difficult to assess the role of change in angular speed or angular size information, since observers can make judgments on the basis of the projected direction of motion. To avoid this problem and to allow us to examine the effects of a scene background, we considered motion paths in which the projected direction of motion was not predictive of the 3-D trajectory (see Fig. 1). Specifically, we examined conditions in which the upward or downward motion trajectories always had a downward-projected motion direction. In Experiment 1, we examined whether observers could use the angular speed and background scene information to determine the direction of motion of an approaching object moving in either an upward or a downward linear trajectory. In Experiments 2, 3, and 4, we examined whether observers could use the angular speed information and background information to discriminate between upward and downward curved trajectories, between upward and downward discontinuous linear trajectories, and between linear and curved trajectories. In Experiment 5, we examined the effect of angular speed and the background scene on discriminating direction of motion, with angular size information consistent or inconsistent with motion in depth.

Experiment 1: Upward versus downward linear trajectories

In the first experiment, we examined the ability of observers to judge whether an approaching object was moving in an upward or a downward trajectory. For both trajectories, the projected motion of the object was always downward. That is, if only the projected motion path is considered, the direction of its motion is ambiguous (see Fig. 1). However, the angular speed function varied for the two trajectories. We examined whether observers could discriminate these motion trajectories using the change in angular speed information alone. To examine whether the background scene was used to determine the change in depth of the object, we manipulated the background scene information by presenting either a 3-D scene background or a uniform background.

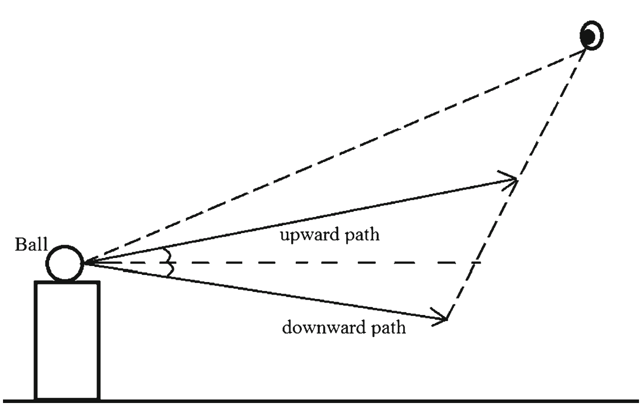

Fig. 1 Schematic of the simulated scene (not to scale). The projected endpoints of the upward and the downward trajectories were matched, and the slopes of the upward and downward trajectories, relative to a line parallel to the ground plane, were the same. The 3-D speed for both trajectories was adjusted such that the motion duration was the same for two trajectories

Method

Observers

The observers were 22 undergraduate students (9 male and 13 female) from the University of California, Riverside. All observers were paid for their participation, were naive regarding the purpose of the experiment, and had normal or corrected-to-normal visual acuity. All participants tested in this and the following experiments provided informed consent before participating.

Stimuli

Each display consisted of a background scene, a digitally inserted cylinder, and a white sphere on top of the cylinder. The purpose of the cylinder (which provided static depth information to the scene) was to provide an initial position of the object that was above the ground plane and to provide information about the position of the sphere in the scene. The background scene was either a uniform gray or a naturalistic scene depicting a large, flat grassy field (see Fig. 2). The picture of the natural scene was taken on a sunny day at a community park.

In the 3-D simulation (programmed using C++ and OpenGL Utility Toolkit), the cylinder measured 0.12 m^2 (base) × 0.3 m (height) and was located at a distance of 18 m from the observer. For each motion trajectory, a white sphere with a radius of 0.08 m was positioned on top of the cylinder and then traveled toward the observers in either an upward or a downward linear path in 3-D with a slope of 0.7°, 1.4°, or 2.1° relative to a line parallel to the ground plane (see Fig. 1). The levels of curvature were selected to represent intermediate to high difficulty levels based on pilot data. The sphere disappeared before reaching the projection plane. The 3-D speed of the sphere was adjusted so that, at each level of slope, the projected endpoint of the upward and downward trajectories matched. That is, the upward and downward motion trajectories had the same projected motion path, but the angular speed function was different for the two motion directions. The position of the starting point, endpoint, and 3-D speed of the sphere at each level of slope for both motion directions are included in Table 1. In order to examine the separate effect of the change in angular speed on the accuracy of judgments of whether the trajectory was upward or downward, the change in angular size was based on a level (horizontal) path regardless of the motion direction (upward or downward) or on the slope of the motion trajectory indicated by the angular speed function. The sphere subtended a visual angle of 0.51° at the start of each motion trajectory (18 m from the observers) and 1.0° at the end of each motion trajectory (9.2 m from the observers) for all conditions. The center

Fig. 2 Examples of stimuli used in Experiment 1 and the control experiment. **a** An object resting on a platform against a 3-D background scene. **b** An object resting on a platform against a uniform background. **c** An object resting on a platform against a scrambled scene (used in the control experiment only)

of the sphere was located at 2.86° below eye height at the start of each motion trajectory and 5.59° below eye height at the end of each motion trajectory.

Design

Two independent variables were manipulated: (1) the background scene (3-D scene or uniform gray) and (2) the slope of the motion trajectory (0.7°, 1.4°, or 2.1°). The background scene was run as a between-subjects variable, and the slope was run as a within-subjects variable. For each observer, each of the three levels of slope was presented for 40 trials. For half of the trials, the upward trajectory was presented first, and for the other half, the downward trajectory was presented first. Twelve practice trials (4 trials for each level of slope) were inserted at the beginning of each block. Observers were assigned randomly to the background scene condition. The order of the trials for each observer was randomized.

Apparatus

The displays were presented on a 52-in. (132 cm) flat screen plasma TV with a pixel resolution of 1,920 ×1,080 , controlled by a Windows 7 Professional Operating System on a Dell Precision T7500 workstation. The refresh rate was 60 Hz. The dimensions of the display on the monitor were 115.1 cm (W) × 64.8 cm (H), subtending a visual angle of 45.3° × 26.4° at a viewing distance of 138 cm. A black circular viewing tube was placed in front of the observer. The viewing tube had a diameter of 3.81 cm and was 4.57 cm long, resulting in a visual angle of 22.6°. A chinrest was mounted at a position appropriate to this viewing distance. An eye patch was used to cover one of the observer's eyes. An optical mouse was used by the observer to initiate each trial and to make responses.

Procedure

The experiment was run in a dark room. The observers viewed the displays monocularly through the viewing tube, with their head position fixed by the chinrest. On each trial, the observer was presented sequentially with two displays. In each display, a cylinder with a sphere on top was presented against either a uniform background or a 3-D scene background. The observer was instructed to fixate the sphere and press the left button of the mouse to initiate the trial. The sphere was positioned on top of the cylinder (static presentation) for 500 ms and then translated toward the observer along a linear trajectory at a constant speed. The sphere traveled for 3 s and then disappeared. One second later, the sphere reappeared on the top of the cylinder to indicate the beginning of the second display. The direction of the simulated trajectory was either upward or downward, with the same slope in each display. The direction of the projected trajectories was always downward relative to the observers' line of sight. The 3-D speed of the two trajectories was adjusted so that the projected endpoints of the two trajectories were matched (see Fig. 1 for illustration). After the second display, the observer was instructed to determine in which of the two displays the sphere traveled along an upward path. The observer made a response by clicking either the left mouse button to indicate that the first display was traveling along an upward path or the right mouse button to indicate that the second display was traveling along an upward path, after which the next trial was initiated. If the observer did not make a response within 5 s, the trial was terminated automatically and was repeated at the end of the block. Feedback was not provided during the practice trials or the experiment.

Results and discussion

The average percent correct was calculated for each observer in each condition and was analyzed in a 2 (background scene) × 3 (slope of motion trajectory) mixed analysis of variance (ANOVA). The main effect of background scene was significant, $F(1, 20) = 8.41$, $p < .01$. The average percent correct was 81.6 % when the motion trajectories were presented against a 3-D scene background and 70.8 % when the motion trajectories were presented against a uniform background. There was also a significant main effect

Table 1 Simulated 3-D starting points, end points, and speeds in Experiment 1

Slope	Start Point (*y*, *z*)	Downward Trajectory		Upward Trajectory	
		End Point (*y*, *z*)	3-D Speed (m/s)	End Point (*y*, *z*)	3-D Speed (m/s)
0.7°	(0.3, 18.0)	(0.20, 10.18)	2.61	(0.42, 7.94)	3.35
1.4°	(0.3, 18.0)	(0.13, 10.96)	2.34	(0.59, 6.27)	3.91
2.1°	(0.3, 18.0)	(0.07, 11.60)	2.14	(0.81, 3.92)	4.70

of slope, $F(2, 40) = 23.76$, $p < .01$. As can be seen in Fig. 3, average percent correct increased as a function of increasing slope for both background scene conditions. The interaction between the background scene and the slope was not significant, $F(2, 40) < 1$, $p > .05$.

In order to examine whether this effect of the background scene was simply due to the 2-D information available in the scene, rather than the 3-D layout information, we conducted a control experiment including a uniform background scene, a 3-D background scene, and a scrambled image. The scrambled image was made by splitting the original 3-D background scene into 32 × 18 squares and randomly repositioning each square. The same levels of slope were examined. Eleven observers participated in the control experiment, and the average percent correct was analyzed in a 3 (background) × 3 (slope of motion trajectory) ANOVA. Again, we found a significant main effect of background scene, $F(2, 20) = 10.15$, $p < .01$. Specifically, the average percent correct for the 3-D scene background was 72.0 %, which was significantly higher than either uniform background (65.4 %) or scrambled image (65.2 %), suggesting that the effect

of the background scene on perceiving direction of motion trajectories was due to 3-D layout information, rather than the 2-D information in the background scene. In addition, we found a significant main effect of slope, $F(2, 20) = 27.89$, $p < .01$. The interaction between background scene and slope did not reach significance, $F(2, 20) = 1.57$, $p = .20$.

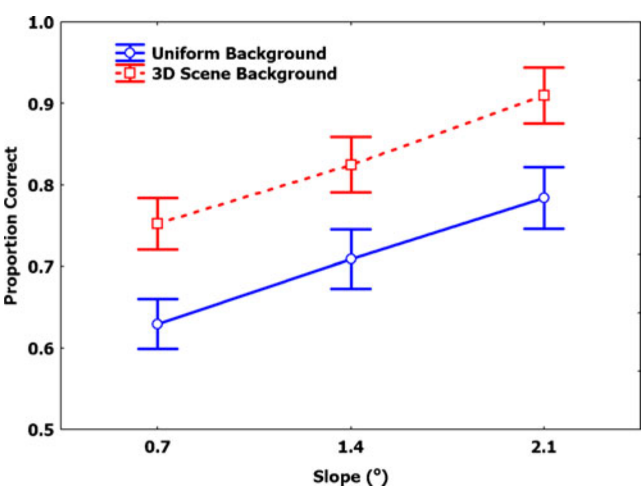

Fig. 3 Percent correct as a function of slope and background scene condition from Experiment 1. Error bars represent ±1 standard error

Overall, the results indicated that observers were able to discriminate the direction of motion trajectories even when the projected path for both trajectories was the same, suggesting that observers use the change in angular speed information to discriminate the direction of motion trajectories. In addition, average performance was 10.8 % higher with a 3-D scene background than with a uniform gray background. The benefit of the 3-D scene background did not vary as a function of slope, suggesting an overall improvement in performance regardless of the slope.

Experiment 2: Discontinuous linear trajectories

In Experiment 1, we found that observers were able to use the change in angular speed and the 3-D scene background information to discriminate the direction (upward or downward) of linear trajectories, with the angular size function based on a level (horizontal) trajectory. For those displays, the angular size function can be thought of as conflicting with the angular speed function. This is unlikely to have affected judgments, because the angular size functions are almost identical for upward, downward, and level trajectories. To be sure that a conflicting angular size function has no effect on these judgments, the present experiment includes conditions in which (1) the angular size function corresponded to the angular speed function (the same direction was indicated by both speed and size), thus avoiding any possible conflict between the two sources of information; (2) the angular size function was consistent with a level (horizontal) linear trajectory (the direction was indicated by speed only), so that size variations could not be used to discriminate upward from downward motion in 3-D; and (3) the angular speed was consistent with a level (horizontal) linear trajectory (the direction was indicated by size only), so that angular speed could not be used to discriminate upward from downward motion in 3-D.

In Experiment 1 we examined linear motion trajectories. In Experiment 2, we examined discontinuous trajectories to determine whether the results obtained in Experiment 1 (with linear trajectories) will generalize to discontinuous trajectories. On each trial, observers were presented with two sequential displays depicting a sphere traveling toward them either in a downward linear trajectory followed by a upward linear trajectory (a "V" shape) or in an upward linear trajectory followed by a downward linear trajectory (an inverted "V" shape). The two linear trajectories had the same beginning and ending positions. The simulated distance and speed for the two trajectories were matched. The task was to determine in which of the two displays the object traveled first upward then downward. Our purpose was to determine the effects of angular speed and background on the accuracy with which observers could discriminate upward–downward from downward–upward discontinuous linear trajectories.

Method

Observers

The observers were 12 undergraduate students (6 male and 6 female) from the University of California, Riverside. All observers were paid for their participation, were naive regarding the purpose of the experiment, and had normal or corrected-to-normal visual acuity. None of the observers had participated in any of the previous experiments.

Stimuli

The stimuli were similar to those used in Experiment 1, except that the cylinder was not presented in the display and the sphere traveled along a discontinuous linear trajectory. On each trial, the sphere either traveled in a downward linear trajectory followed by an upward linear trajectory (a "V" shape) or traveled in an upward linear trajectory followed by a downward linear trajectory (an inverted "V" shape). The two trajectories had the same starting and ending points. The slope was the same for each segment of the trajectories in both displays.

Design

Three independent variables were manipulated: (1) the background scene (3-D scene or uniform gray), (2) the source of information indicating the direction of motion (changes in angular speed and angular size, change in angular speed only, or change in angular size only), and (3) the slope of the motion trajectories (0.41°, 0.83°, or 1.24°). The background scene variable was run in two separate blocks to avoid potential carryover effects (the effect of the scene on one trial affecting performance on a subsequent trial) from trial to trial. Fourteen replications of each combination of information source and curvature level were presented in each block. For half of the trials, the upward–downward trajectory was presented first, whereas for the other half, the downward–upward trajectory was presented first. Six practice trials (two trials for each level of information source) were inserted at the beginning of each block. The order of background conditions was counterbalanced across observers. The order of the trials for each observer in each block was randomized.

Apparatus and procedure

The apparatus and procedure were similar to those used in Experiment 1. On each trial, two displays simulating a sphere moving toward the observer were presented sequentially. One display simulated a sphere traveling first upward and then downward, and the other display simulated a sphere traveling first downward and then upward. The observers' task was to determine in which of the two displays the sphere was traveling first upward and then downward. They responded by pressing one of the two mouse buttons. Feedback was not provided during the practice trials or the experiment.

Results and discussion

The average percent correct was calculated for each observer in each condition. These data were analyzed in a 2 (background) × 3 (source of information) × 3 (slope level) ANOVA. Similar to Experiment 1, we found a significant main effect of background type, $F(1, 11) = 8.84$, $p < .05$. The average percent correct with a 3-D scene background was 69.3 %, whereas the average percent correct with a uniform background was 64.1 %. There were significant main effects of information source, $F(2, 22) = 31.82$, $p < .01$, and slope, $F(2, 22) = 14.71$, $p < .01$, and a significant interaction between the two variables, $F(4, 44) = 8.48$, $p < .01$. As is depicted in Fig. 4, when the information available about motion direction consisted of changes in both angular size and angular speed or changes in angular speed only, the average percent correct increased with increasing slope level and with a 3-D scene background. This result suggests that observers were using the angular speed and background information to determine the direction of the motion trajectories. However, when the information available about the trajectories was change in angular size only, the average percent correct was at a chance level (50 %) regardless of theslope level or the background. Changes in angular size did not affect accuracy of the discrimination. No other interaction reached significance ($p > .05$).

Experiment 3: Upward versus downward curved trajectories

In Experiments 1 and 2, we showed that observers could use the change in angular speed to discriminate the direction of

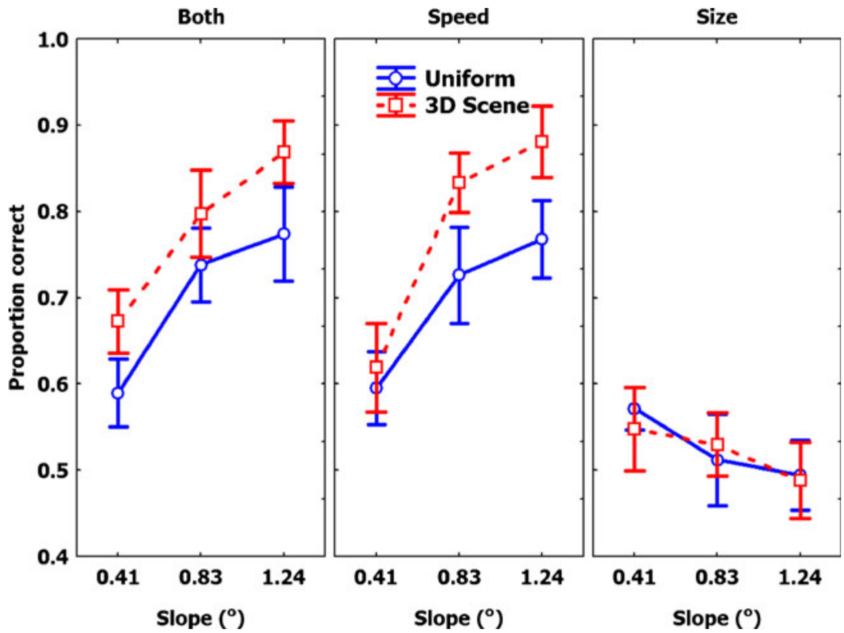

Fig. 4 Proportion correct as a function of slope, source of information indicating direction of motion, and background scene from Experiment 2. Error bars represent ±1 standard error

linear trajectories. In addition, the presence of a 3-D background scene improved observers' performance, as compared with a uniform background scene. In the present experiment, we examined whether this effect would generalize to upward and downward curved trajectories. The two curved trajectories had the same beginning and ending positions. The simulated distance and speed for the two trajectories were matched.

Method

Observers

The observers were 12 undergraduate students (5 male and 7 female) from the University of California, Riverside. All observers were paid for their participation, were naive regarding the purpose of the experiment, and had normal or corrected-to-normal visual acuity. Three of the observers had participated in Experiment 1; their performance was not significantly different from the performance of the remaining observers in Experiment 3.

Stimuli

The stimuli were similar to those used in Experiment 2, except that the sphere was traveling in curved trajectories. At the beginning of the motion trajectory, the sphere was positioned 12 m away from the observer and 0.3 m above the ground plane and subtended a visual angle of 0.76°. The sphere then traveled toward the observers in either an upward or a downward curved trajectory. The endpoint of the trajectories was 4.2 m away from the observer and 0.3 m above the ground plane. The sphere subtended a visual angle of 2.18° at the endpoint. The curvature of the trajectory was 0.0074 m^{-1}, 0.0098 m^{-1}, or 0.0123 m^{-1}. The levels of curvature were selected to represent intermediate to high difficulty levels on the basis of pilot data. The direction of projected motion was downward in all displays.

Design

Three independent variables were manipulated: (1) the background scene (3-D scene or uniform gray), (2) the sources of information indicating the direction of curvature (changes in both angular speed and angular size, changes in angular speed only, or changes in angular size only), and (3) the curvature level (0.0074 m^{-1}, 0.0098 m^{-1}, or 0.0123 m^{-1}). The background scene variable was run in two separate blocks to avoid potential carryover effects from trial to trial. In each block, each of the nine combinations of information source and curvature was repeated 16 times. On half of the trials, the upward curved trajectory was presented first, whereas for the other half, the downward curved trajectory was presented first. Six practice trials (two trials for each level of information source) were inserted at the beginning of each block. The order of background scenes was counterbalanced across observers. The order of the trials for each observer in each block was randomized.

Apparatus and procedure

The apparatus and the procedure were similar to those used in Experiment 1. On each trial, two displays of a white sphere moving toward the observer were presented sequentially. The two displays depicted an upward and downward trajectory. The task of the observer was to determine in which of the displays the sphere was traveling in an upward curved trajectory. The observer responded by pressing one of the two mouse buttons. Feedback was not provided during the practice trials or the experiment.

Results and discussion

The average percent correct was calculated for each observer in each condition. These data were analyzed in a 2 (background) × 3 (source of information) × 3 (curvature level) ANOVA. The main effect of background was significant, $F(1, 11) = 11.08$, $p < .01$. According to this result, the overall average percent correct with a 3-D scene background (65.9 %) was significantly higher than with a uniform background (60.6 %) (see Fig. 5). This suggests that observers wereusing the 3-D background information in their judgments of the direction of the motion trajectories. There was a significant main effect of information source, $F(2, 22) = 25.32$, $p < .01$, a significant main effect of curvature, $F(2, 22) = 14.70$, $p < .01$, and a significant interaction between these two variables, $F(4, 44) = 3.01$, $p < .05$. When the information for curvature was the change in angular speed or both the change in angular speed and angular size, the average percent correct increased with increasing curvature. In addition, the average percent correct was higher with a 3-D scene background, as compared with a uniform background. However, when the information for curvature was the change in angular size only, the average percent correct was at chance (50 %), regardless of the curvature level or the type of background. Changes in angular size, which were nearly identical for the two displays in a pair, did not affect the accuracy of the discriminations. The interaction between curvature and background scene did not reach significance, $F(2, 22) = 2.90$, $p = .08$. No other main effect or interactions were significant ($p > .05$).

Experiment 4: Linear versus curved trajectories

In Experiment 3, we found that observers were able to use change in angular speed information and background scene information to discriminate upward and downward curved trajectories. The purpose of the present experiment was to determine whether the effects of speed and background would generalize to other judgments of trajectories in 3-D scenes. In order to examine this issue, in the present experiment, we examined the effects of changes in angular speed and background information on the ability of observers to discriminate between linear and curved trajectories. On each trial, observers were presented two displays, one depicting a sphere traveling in a linear trajectory and the other depicting a sphere traveling in either an upward or a downward curved trajectory. The task was to determine which of the two displays depicted a curved trajectory. Similar to the previous experiments, the source of information indicating curvature, the background scene, and curvature level were manipulated.

Method

Observers

The observers were 10 undergraduate students (4 male and 6 female) from the University of California, Riverside. All observers were paid for their participation, were naive regarding the purpose of the experiment, and had normal or corrected-to-normal visual acuity. None of the observers had participated in any of the previous experiments.

Stimuli

The stimuli were similar to those used in Experiment 2, except that on each trial, one of the displays presented a sphere traveling along a linear trajectory and the other display presented a curved trajectory. The direction of projected motion was downward in both displays. The two trajectories had the same starting and ending points.

Design

Four independent variables were manipulated: (1) the background scene (3-D scene or uniform gray), (2) the curvature direction (upward or downward curvature), (3) the source of information indicating the type of trajectory (changes in both angular speed and angular size, change in angular speed only, or change in angular size only), and (4) the curvature level (0.0037 m^{-1}, 0.0074 m^{-1}, or 0.0111 m^{-1}). The levels of curvature were selected to represent intermediate to high difficulty levels on the basis of pilot data. The background scene variable was run in two separate sessions to avoid potential carryover effects from trial to trial. In each session, each of the 18 combinations of curvature direction, source of information, and curvature level was repeated 12 times. This resulted in a total of 288 trials per session, which was divided into two blocks. For half of the trials, the linear trajectory was presented first, whereas for the other half, the curved trajectory was presented first. Six practice trials (two trials for each level of information source) were inserted at the beginning of each block. The order of background scene condition was counterbalanced across observers, and the order of the trials for each observer in each block was randomized.

Apparatus and procedure

The apparatus and procedure were similar to those used in Experiment 2. On each trial, observers were presented

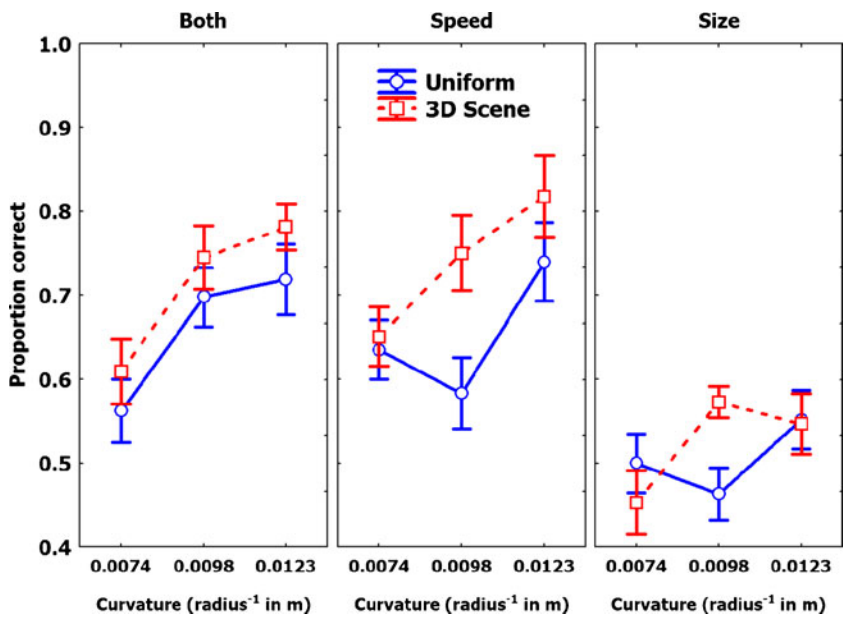

Fig. 5 Proportion correct as a function of curvature, information source indicating curvature, and background scene from Experiment 3. Error bars represent ±1 standard error

sequentially with two displays of a sphere moving toward the observer below eye level. One of the displays simulated a sphere traveling along a linear trajectory parallel to the ground, and the other display simulated a sphere traveling along either an upward curved trajectory or a downward curved trajectory. The task of the observers was to determine in which of the two displays the sphere was traveling in a curved path. They responded by pressing one of the two mouse buttons. Feedback was not provided during the practice trials or the experiment.

Results and discussion

The average percent correct was calculated for each observer in each condition. These data were analyzed in a 2 (background) × 2 (curvature direction) × 3 (source of information) × 3 (curvature level) ANOVA. There was a significant main effect of curvature direction, $F(1, 9) = 20.69$, $p < .01$, a significant main effect of information source, $F(2, 18) = 21.73$, $p < .01$, a significant interaction between these two variables, $F(2, 18) = 25.98$, $p < .01$, and a significant three-way interaction between background type, curvature direction, and information source, $F(2, 18) = 4.41$, $p < .05$ (see Fig. 6). A simple analysis was conducted at each level of information source. There was a significant interaction between background type and curvature direction when the motion trajectory was specified by changes in both angular speed and angular size, $F(1, 9) = 7.79$, $p < .05$, but not when the motion trajectory was specified by changes in angular speed only, $F(1, 9) = 1.20$, $p = .30$, or by changes in angular size only, $F(1, 9) = 2.82$, $p = .13$. A further simple analysis was conducted to examine the effect of background scene at each level of curvature direction when the motion trajectory was specified by changes in both angular speed and angular size. When the motion trajectory was curved upward, the average percent correct was significantly higher with a 3-D scene than with a uniform scene, $F(1, 9) = 7.27$, $p < .05$. When the motion trajectory was curved downward, however, there was no significant main effect of background scene, $F(1, 9) = 2.51$, $p = .15$. These results suggest that the rate of change in size and velocity, available in the curved trajectory conditions of the present study, can be more accurately recovered when a background is present.

In addition, we found a significant main effect of curvature level, $F(2, 18) = 14.17$, $p < .01$, and a significant interaction between curvature level and source of information, $F(4, 36) = 2.88$, $p < .05$. As can be seen from Fig. 6, when the information available about curvature was changes in both angular speed and angular size or changes in angular speed only, the average percent correct increased with increasing curvature level. In addition, the average percent correct was generally higher with a 3-D scene background than with a uniform background. However, when the information available about curvature was change in angular size only, the average percent correct was at a chance level (50 %), regardless of the curvature level or the background. No other main effect or interaction was significant ($p > .05$).

Overall, our results suggest that the observers' ability to discriminate curved from linear trajectories was better for upward than for downward motion. Judgments in the upward curvature condition were more accurate with a scene background than with a uniform background.

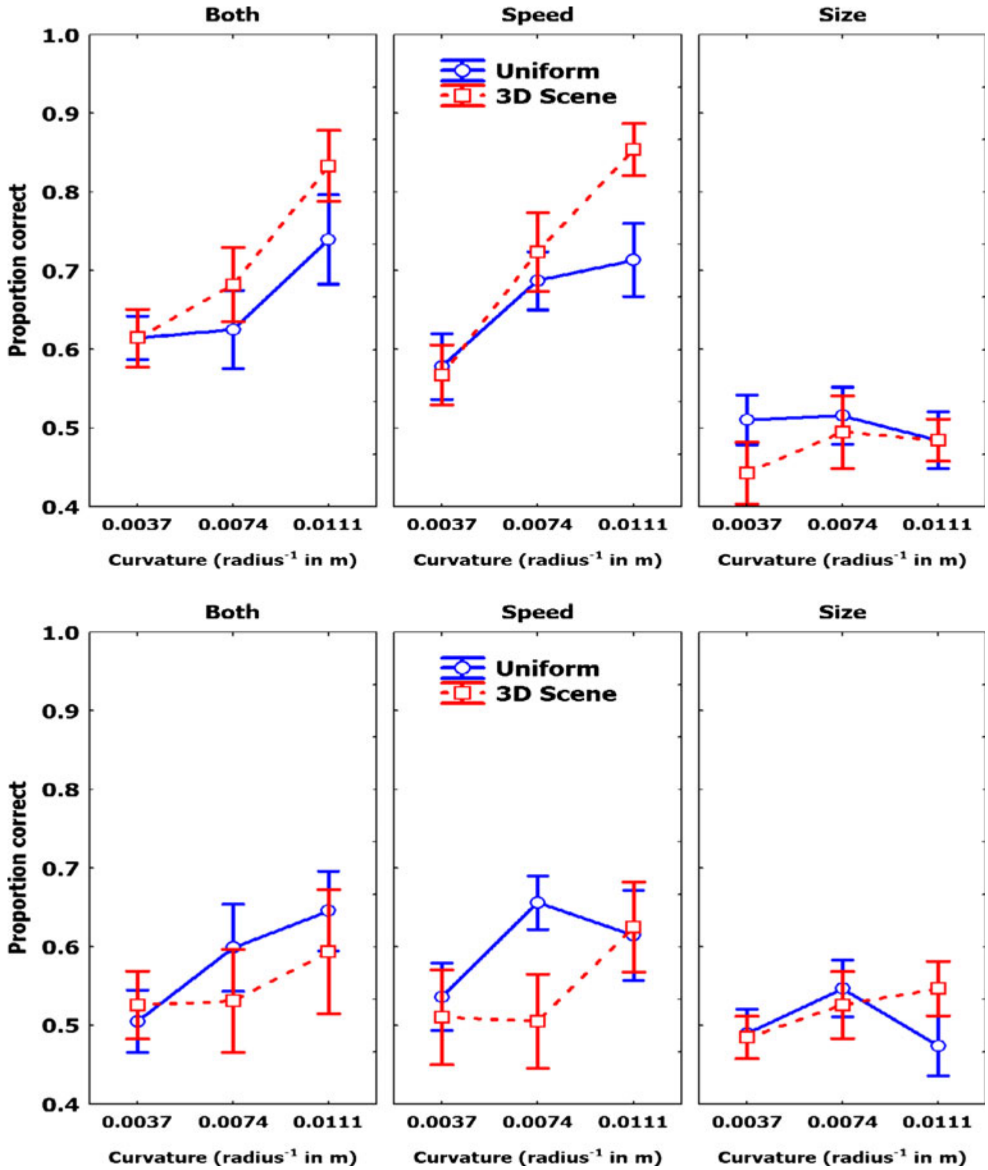

Fig. 6 Proportion correct as a function of curvature level, direction of curvature, source of information indicating motion direction, and background scene from Experiment 4. Top and bottom panels show results for upward and downward curvatures, respectively. Error bars represent ±1 standard error

Experiment 5: Constant 3-D size versus constant 2-D size

In Experiment 1, the angular size function was based on a horizontal trajectory. In Experiments 2–4, the angular size function either was based on the same trajectory as the angular speed function or was based on a trajectory intermediate between the two trajectories being discriminated. Each of the trajectories used to determine the angular size function displayed the same overall motion in depth as the trajectories being discriminated, and which angular size function was used did not affect the accuracy of the judgments as long as the angular speed function provided the information necessary for the discrimination. The present experiment addresses the question of whether it is important to use an angular size function that is consistent with motion in depth, even if this function is the same for the two displays being discriminated.

Method

Observers

The observers were 11 undergraduate students (5 male and 6 female) from the University of California, Riverside. All observers were paid for their participation, were naive regarding the purpose of the experiment, and had normal or corrected-to-normal visual acuity. None of the observers had participated in any of the previous experiments.

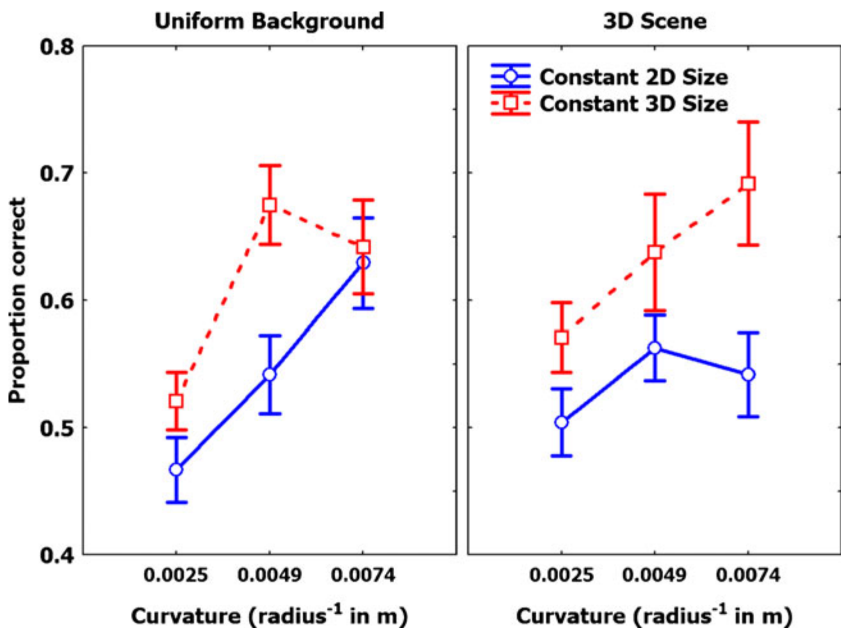

Fig. 7 Proportion correct as a function of background scene, curvature level, and size from Experiment 5. Error bars represent ±1 standard error

Stimuli

The stimuli were similar to those in Experiment 2, except that the angular speed function for all displays was based on the simulated magnitude and direction of curvature, whereas the angular size either was based on an intermediate linear path in depth (constant in 3-D) or was fixed during a display (constant in 2-D). For the constant 2-D size condition, the angular size of the sphere was the median of the angular sizes in a display in the constant 3-D size condition. The direction of projected motion was downward in all displays, and all displays had the same starting and ending points in the 2-D projection.

Design

Three independent variables were manipulated: (1) the background scene (3-D scene or uniform gray), (2) object size (constant 3-D or constant 2-D), and (3) the curvature level (0.0025 m^{-1}, 0.0049 m^{-1}, or 0.0074 m^{-1}). The levels of curvature were selected to represent intermediate to high difficulty levels on the basis of pilot data. The background scene variable was run in two separate sessions to avoid potential carryover effects from trial to trial. In each session, 20 replications of six combinations of object size and curvature level were presented. This resulted in a total of 120 trials per block. For half of the trials, the downward curved trajectory was presented first, whereas for the other half, the upward curved trajectory was presented first. Six practice trials (1 trial for each of the six combinations) were inserted at the beginning of each block. The order of background scene conditions was counterbalanced across observers, and the order of the trials for each observer in each block was randomized.

Apparatus and procedure

The apparatus and procedure were similar to those used in Experiment 3. On each trial, two displays, each simulating a sphere moving toward the observer below eye level, were presented sequentially. Both displays in a pair had the same curvature level and the same type of size change (constant 3-D or constant 2-D). In one of the displays, the sphere was traveling in an upward curved trajectory in 3-D; in the other display, the sphere was traveling in a downward curved trajectory. The task of the observers was to determine in which of the two displays the sphere was traveling in an upward curved trajectory. They responded by pressing one of the two mouse buttons. Feedback was not provided during the practice trials or the experiment.

Results and discussion

The average percent correct was calculated for each observer in each condition. These data were analyzed in a 2 (background) × 2 (type of size information) × 3 (curvature level) ANOVA.

There was a significant main effect of size, $F(1, 10) = 9.29$, $p < .05$, suggesting that even when size information is not directly relevant to the discrimination, accuracy is greater with size changes consistent with motion in depth than with a constant 2-D size. There was also a main effect of curvature level, $F(2, 20) = 24.58$, $p < .01$. The main effect of background scene was not significant, $F(1, 10) < 1$, $p > .05$, but there was a significant interaction between size and background scene, $F(1, 10) = 8.25$, $p < .05$. A simple effect test was conducted on each level of background scene. We found that with a uniform background, there was no significant difference between constant 3-D size and constant 2-D size, $F(1, 10) = 3.97$, $p = .07$. When a 3-D scene was presented, percent correct was significantly higher with a constant 3-D size than with a constant 2-D size, $F(1, 10) = 13.71$, $p < .01$ (see Fig. 7). No other main effect or interaction reached significance ($p > .05$).

General discussion

The visual system has available three sources of information to recover motion trajectories of objects in 3-D scenes: (1) changes in the angular speed and angular size of an object's projection, (2) binocular information based on the rate of change in disparity and vergence, and (3) background scene information that can be used to determine the depth and layout of objects in a scene and how this changes during object motion. In the present study, we examined the use of background scene information in discriminating direction of object motion trajectories and how background scene information interacts with changes in angular speed and angular size.

In Experiment 1, we presented observers with a sphere traveling from an initial location at a fixed distance toward the observers either in an upward linear trajectory or in a downward linear trajectory. The starting and ending points of the two trajectories were matched in the projection, and the change in angular size for both trajectories corresponded to a level trajectory. The motion trajectories were presented against either a 3-D scene background or a uniform background. We found that observers were able to use the change in angular speed information to discriminate the direction of motion and that their performance was improved with a 3-D scene background, as compared with a uniform background.

In Experiments 2–4, we examined the ability of observers to discriminate between discontinuous linear trajectories, discriminate between upward and downward curved trajectories, and discriminate between curved and linear trajectories. In each experiment, the starting and end points of the trajectories were matched both in the simulation and in the projection. Angular speed information was sufficient for accurate discriminations of the direction of motion trajectories, with changes in angular size either consistent with each of the two trajectories being discriminated or based on an intermediate trajectory. In both cases, angular size changes indicated motion in depth. To examine whether discriminations based on angular speed are affected by the angular size information, we presented observers with displays in which either the simulated object size was constant in 3-D and the angular size varied with the simulated distance or the angular (2-D) size was constant (Experiment 5). We found improved performance with a constant 3-D size, as compared with a constant 2-D size, suggesting that changes in angular size do affect judgments of the direction of motion for these trajectories.

Overall, our results showed that observers were able to use changes in angular speed and the information from a 3-D scene background in determining object motion trajectories in depth and that this effect was consistent for linear, discontinuous linear, and curved trajectories. These results indicated the robustness of these information sources for the perception of motion trajectories in 3-D scenes. In addition, this advantage of the 3-D scene background was not simply due to the 2-D information available in background scenes. When we presented observers with a scrambled 3-D scene with global depth information removed, performance was the same as occurred when a uniform background was presented (Experiment 1). Our results are consistent with previous studies demonstrating the effect of pictorial depth cues on motion judgments such as judging time to contact (DeLucia & Warren, 1994), judging object motion trajectory (Warren & Rushton, 2009), and judging velocity (Rushton & Duke, 2009), suggesting that the background scene information plays an important role in recovering motion trajectories. Background surfaces, especially the ground surface, mediate the perceived layout of objects resting on the surface or connected to the surface through nested contact relations. As was discussed earlier, perceived angle of approach of an object could be derived from the projected path of the object and the absolute distance of the moving object. Geometrically, there are at least two ways that absolute distance of an object in a 3-D scene is derived: (1) using eye height and angle of declination of the object, and (2) using eye height and the texture gradient on the ground surface. Previous studies have provided support for both mechanisms (e.g., Ooi, Wu, & He, 2001; Sinai, Ooi, & He, 1998). The results of the present study suggest the importance of texture gradients on a ground surface for judging motion trajectories. There are, of course, several different sources of information from a scene that might be important for the perception of 3-D motion trajectories. An important question for future research is how the perception of object motion trajectories is affected by perceived eye height, perceived angle of declination, or variations in texture gradients and the relative importance of these information sources. In addition, an issue not addressed in the present study is the importance of surface information defined from texture gradients, as compared with surface information from a horizon and a uniform texture. Examining the effect of these factors on the perceived trajectories of moving objects when a scene is present will help us further understand the visual processes that combine background scene information with change in angular speed and angular size information.

In addition to changes in angular speed, angular size, and background scene information, another source of information that may specify the motion trajectory is the change in vergence and disparity of a moving object (Rushton, 2004). According to the model proposed by Rushton, the angle of approach of an object could be determined using the interocular separation of the eyes, the angular speed of the object on both eyes, and the distance of the object from the observers. An important topic for future research is to examine how binocular information is combined with change in angular speed and angular size and with background scene information to recover object motion trajectories.

In summary, the results of the present study indicate that, as an object travels in space, observers can use the change in angular speed and background scene information to determine the motion trajectory of the object when binocular information is not present. Judgments based on angular speed are more accurate when changes in angular size are consistent with motion in depth than when a constant angular size is displayed.

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