Published in final edited form as:

Atten Percept Psychophys. 2013 January ; 75(1): 68–82. doi:10.3758/s13414-012-0367-z.

Effects of changes in size, speed and distance on the perception of curved 3D trajectories

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Abstract

Previous research on the perception of 3D object motion has considered time to collision, time to passage, collision detection and judgments of speed and direction of motion, but has not directly studied the perception of the overall shape of the motion path. We examined the perception of the magnitude of curvature and sign of curvature of the motion path for objects moving at eye level in a horizontal plane parallel to the line of sight. We considered two sources of information for the perception of motion trajectories: changes in angular size and changes in angular speed. Three experiments examined judgments of relative curvature for objects moving at different distances. At the closest distance studied, accuracy was high with size information alone but near chance with speed information alone. At the greatest distance, accuracy with size information alone decreased sharply but accuracy for displays with both size and speed information remained high. We found similar results in two experiments with judgments of sign of curvature. Accuracy was higher for displays with both size and speed information than with size information alone, even when the speed information was based on parallel projections and was not informative about sign of curvature. For both magnitude of curvature and sign of curvature judgments, information indicating that the trajectory was curved increased accuracy, even when this information was not directly relevant to the required judgment.

Human observers are able to use the information in projections of 3D motion to make judgments about the trajectories of objects moving in the 3D world. Accurate perception of object motion in 3D is important in many real world applications, such as traffic safety and sports. Much of the research on the perception of motion trajectories has been concerned with the accuracy of judgments about approaching objects, such as time to contact (Lee, 1976), time to passage (Kaiser & Mowafy, 1993; Kaiser & Hecht, 1995), collision detection (Gray & Regan, 1998; Andersen, Cisneros, Atchley, & Saidpour, 1999; Regan & Gray, 2000; Ni & Andersen, 2008), speed and direction of motion (Harris & Drga, 2005; Brooks & Stone, 2006; Rushton & Duke, 2009), and the prediction of the future trajectory (Craig, Berton, Rao, Fernandez, & Bootsma, 2006; Craig et al., 2009). The types of information that have been studied include optical motion, to be discussed below, binocular disparity (Rushton & Wann, 1999; Rushton & Duke, 2007; Warren & Rushton, 2009), and scene-based information (Meng & Sedgwick, 2001, 2002; Ni, Braunstein & Andersen, 2004, 2005).

Gibson demonstrated that observers can pick up many aspects of motion in the 3D world from 2D optical patterns (Gibson, 1950; Gibson, 1966; Gibson, 1979). Mathematical analyses have indicated that properties of 3D motion can be recovered from optical motion alone (Todd, 1981; Regan & Kaushal, 1994). When optical motion is the only information available, properties of the motion can in theory be recovered from changes in angular size and changes in projected position. Todd (1981) showed that if the distance from a planar projection surface to the observation point is set to unity, and object rotation is not considered, the object's approach angle (γ) relative to the horizontal axis is given by:

$$\tan \gamma = Y - R^* VY / VR \quad (1)$$

where Y is the vertical projected distance from the edge of the object to the observer, R is the projected width of the object and VY and VR are the time derivatives of Y and R . Equation 1 indicates that the trajectory of the object's motion can be recovered in principle from optical motion alone. Regan and Kaushal (1994) also proposed that the direction of motion in depth can be quantified from information in a monocular retinal image. Specifically, the direction of motion (β) is determined by the projected translational velocity (Φ) and the rate of projected expansion (θ) of the object:

$$\tan \beta \approx (d\phi/dt)/(d\theta/dt)^* s/d \quad (2)$$

where s is the width of the object and d is the viewing distance. In Todd's (1981) analysis, because the projected path of the moving object was on the vertical midline between the two eyes, VY can be considered to be the angular speed of the moving object. Thus in equations 1 and 2, the ratio between the angular speed and the angular size is a major source of information that is potentially available for determining the direction of motion.

These studies have provided important information about judgments related to motion trajectories in 3D but have not directly examined the perception of the motion path itself. The present study considers the perception of the trajectory of an object moving in 3D. Specifically, we consider information relevant to the perceived curvature of a 3D motion trajectory, including judgments of both the magnitude of curvature and sign of curvature. Of particular interest is the relation between size and speed changes in the projection of an object moving in 3D and how this relation changes with distance. Only a few studies of the perception of object motion in depth have manipulated angular size and speed separately. In one such study, Todd (1981) kept angular size constant and found accuracy to be low for trajectory judgments made without size information. In another study, Gray and Regan (1999) found that elimination of angular size information for an approaching multi-dot pattern could cause an overestimation of the time-to-contact. Also in most studies of 3D object motion, the distance from the object to the observer was not far. In some studies (Ni & Andersen, 2008) the initial position of the object was far from the observer, but the final position was close to the observer. Other studies investigated the effects of different distances (Rushton & Duke, 2009) but did not include distances large enough to greatly reduce perspective effects (variations in angular size and speed resulting from variations in simulated distance) during the motion of the object.

The aim of the present study was to examine the relation between angular size, angular speed and simulated viewing distance in the perception of motion trajectories. Viewing distance determines the amount of perspective information available in a display. Perspective can be defined as "the ratio of the projection of a distance on the closest X-Y plane to the projection of the same distance on the most distant X-Y plane (Braunstein, 1962, p. 415)." This is equivalent to the ratio of the distance from the eye to the most distant plane to the distance from the eye to the closest plane. As the viewing distance increases, the

perspective ratio approaches 1. This projection is referred to as a parallel projection. In a parallel projection, the horizontal and vertical coordinates in the projected image are the same as the horizontal and vertical coordinates in 3D, except for an overall scale factor that is independent of distance. The angular size does not provide information about relative distance in a parallel projection. On the other hand, if the perspective ratio is greater than 1, the angular size varies with distance and the projection is referred to as a perspective projection. Unlike angular size, angular speed is informative about some aspects of motion in depth—in particular about the magnitude of the curvature of a motion path—in both perspective and parallel projections (Todd, 1984). For these reasons we expected a difference in the relative accuracy of judgments based on angular size and judgments based on angular speed as the simulated distance from the observer to the moving object was varied. Figure 1 illustrates the changes in angular size and speed that occur when an object follows a curved path perpendicular to the line of sight. In a perspective projection, angular size increases and then decreases or decreases and then increases, depending on whether the path is convex or concave relative to the observer. In a parallel projection, there is no change in angular size. Angular speed, on the other hand, is affected by curvature in both perspective and parallel projections. Regardless of the sign of curvature and type of projection, angular speed first increases and then decreases. Note that the angular speed function is different for perspective projections of convex and concave paths, but is identical for parallel projections of these paths. Parallel projections do not occur in direct vision, but are approximated when viewing distant objects.

We expected that at a near distance, with relatively large variations in both angular size and angular speed with changes in distance due to strong perspective effects, observers would be highly accurate in judging the path of a moving object. We expected accuracy to remain high with angular size alone if there is a strong constraint to see the moving object as maintaining a constant 3D size. Accuracy with angular speed would be expected to be lower based on previous results (Todd, 1981; Gray & Regan, 1999) that found distortions of perceived depth for displays containing angular speed information but lacking angular size information. This may reflect a weaker constraint to perceive an object as maintaining a constant 3D speed. At a greater distance, because the effects of variations in distance on angular size are reduced, angular size should be less effective for judgments of relative distance. Thus accuracy with both angular size and angular speed, or with angular size alone, should drop to a lower level.

In the present study we simulated the motion of a sphere traveling in a circular arc in a horizontal plane at eye level. Our use of trajectories at eye level was necessary to maintain a constant projected path, avoiding changes in the projected path related to viewing distance. The projected path was always a straight horizontal line with the object moving from left to right. In 3D, however, the paths could be curved differently. For example, in Figure 2, trajectory a is convex (first moving towards the observer and then away from the observer). Trajectory b is also convex but less curved. Trajectory c is concave but with the same magnitude of curvature as trajectory a. The projected trajectories are identical in each case, however. Thus only the angular size and angular speed functions are informative about the magnitude and sign of the curvature.

The present study used two types of judgments to determine the effect of variations in angular size and speed and simulated distance on the perception of the curvature of motion trajectories. In one type of judgment the observer was asked to judge which of two trajectories was more curved, with both trajectories curved in the same direction. In the second type of judgment the observer was asked to determine which of two trajectories was convex and which was concave, with both trajectories having the same magnitude of curvature. Five experiments were conducted. Experiment 1 examined the effectiveness of

angular size information, angular speed information, and both angular size and speed information on judgments of relative curvature magnitude at different distances. In Experiment 2, the effect of displaying angular size information with speed changes based on parallel projections was examined for relative magnitude judgments. In Experiment 3, size information was combined with speed information that was either relevant or irrelevant to the discrimination. Similarly, speed information was combined with size information that was either relevant or irrelevant to the discrimination. Experiments 4 and 5 considered the accuracy of judging the sign of curvature from size and speed information. In Experiment 4 both size and speed changes were based on the same perspective effects (the same simulated viewing distances), whereas in Experiment 5 perspective size information was combined with speed information based on parallel projections.

Experiment 1a—Curvature discrimination: Convex curvatures

Method

Stimuli—Observers were presented with computer-generated displays simulating the motion of a sphere in a horizontal plane at eye level. A sphere was used because it does not change its projected shape with changes in orientation. In each display, the sphere moved along a convex circular arc centered about the line of sight, first moving toward the observer and then moving away from the observer. The motion was in a horizontal plane at eye level. The arcs were from circles with radii of 27.9, 37.6 or 412.2 cm and the curvatures were therefore .036, .027 and .0024 cm^{-1} . Figure 3 shows superimposed frames from displays with convex trajectories varying in curvature (curvature levels 1 and 3) and a concave curvature (curvature level 3).

The simulated viewing distance was either 183, 366 or 549 cm. The simulated distance from the projected plane to the center of the most curved trajectory was 23 cm. The horizontal extent of the motion was 55 cm. Figure 4 shows top views of the trajectories and of the relative positions of the observer and the trajectories. In order to have the motion path subtend the same visual angle at all the three viewing distances, the projection planes at the two greater distances were magnified on the screen. Specifically, the projected plane was magnified 200% at the medium distance and 300% at the furthest distance. (The effects of perspective are determined by the simulated viewing distances. Magnifying the image without changing the physical viewing distance does not alter the perspective information in the scene and is similar to viewing a scene through a telescope.) In each display, the curvature of the sphere's trajectory was indicated either by changes in both its angular size and angular speed, by changes in the angular size only, or by changes in the angular speed only. When the curvature was indicated by changes in angular size only, the angular speed was constant during the motion. When the curvature was indicated by changes in angular speed only, the angular size was constant during the motion. The initial size of the sphere and the initial 3D motion speed were randomly determined for each display so that judgments could not be based on the maximum or minimum angular size or speed. The initial size was selected in the range of 0.8 degrees and 2.3 degrees of visual angle. The initial speed was selected so that the duration of the motion was between 1.5 s and 4.3 s. These ranges were selected to avoid extremes in angular size or speed during the motion sequences.

Observers—The observers were 11 undergraduates from the University of California, Irvine, who received extra credit in a class for participating. All observers had visual acuity (corrected if required) of at least 20/40 (Snellen Eye Chart) and were naïve about the purpose of the experiment.

Apparatus—The displays were computer-generated and presented on a 46-inch (117 cm) LCD monitor at a resolution of 1920×1080 with a refresh rate of 60 Hz. Observers viewed the displays monocularly through a viewing tube in a darkened room. The actual distance from the observer's eye to the monitor was 183 cm. At this distance the effectiveness of accommodation as a flatness cue should be minimal. Black cloth was placed around the monitor and viewing tube to assure that the monitor was visible only through the viewing tube. The viewing tube limited the field of view to an area within the monitor. The frame of the monitor was not visible. The observer's task was to judge which of the two trajectories displayed on each trial appeared to be more curved. The observer responded by pressing the left mouse button to select the first display or the right mouse button to select the second display.

Design—There were two independent variables: the simulated viewing distance (183 cm, 366 cm or 549 cm) and the type of information in the display specifying the curvature of the sphere's motion trajectory. The motion information consisted of changes in angular size only, changes in angular speed only, or changes in both angular size and speed. The changes in angular size and speed for three curvature levels and three simulated viewing distances are shown in Figure 5. On each trial two displays were presented sequentially. The simulated viewing distance and type of information was the same in both displays in a pair, but the displays differed in the curvature of the motion path. Labeling the three levels of curvature as 1, 2 and 3 (1 is the least curved and 3 is the most curved), the comparison on a trial was either between 1 and 2, 1 and 3, or 2 and 3, with the order of displays in a pair counterbalanced. Thus there were 27 types of trials (3 simulated viewing distances $\times$ 3 types of information $\times$ 3 curvature comparisons). There were 11 blocks of 27 trials in the experiment, with a two-minute rest period between blocks. The first block was a practice block and was not used in the data analysis.

Results and discussion

Accuracy of judgments of at least 70% at the closest simulated distance, with both size and speed information available, was used as a criterion for performing the task correctly. Two of the 11 participants did not meet this criterion and their data were excluded from the analysis.

The dependent variable was the accuracy of the judgments. Accuracy (proportion of correct judgments across paired displays) as a function of simulated viewing distance and type of motion information is shown in Figure 6a. Accuracy was analyzed by a repeated measures ANOVA. The same statistical method was used in each of the following experiments.

The ANOVA found significant main effects for both viewing distance, $F(2, 16) = 24.4$, $p < .01$, and motion information, $F(2, 16) = 18.3$, $p < .01$, and a significant interaction between the two variables. $F(4, 32) = 4.39$, $p < .01$. At the closest distance, accuracy with speed information alone was lower than accuracy with either size information alone, $F(1, 8) = 29.1$, $p < .01$, or with both size and speed information, $F(1, 8) = 31.74$, $p < .01$. Accuracy with size information alone declined with increasing viewing distance, $F(2, 16) = 23.4$, $p < .01$, whereas accuracy with speed information alone did not vary significantly across viewing distances, $F(2, 16) = 1.21$, $p > .05$. At the greatest viewing distance, accuracy with both size and speed information was higher than accuracy with either size information alone, $F(1, 8) = 15.8$, $p < .01$, or speed information alone, $F(1, 8) = 15.4$, $p < .01$.

Experiment 1b— Curvature discrimination: Concave curvatures

Method

The method was the same as in Experiment 1a, except that the sphere moved in a concave arc, first away from the observer and then towards the observer. Eleven naïve observers from the same population participated. The visual acuity requirement was the same.

Results and discussion

Two of the 11 participants did not meet the criterion of 70% accuracy at the nearest distance with both types of information present and their data were excluded from the analysis. The results are shown in Figure 6b. The ANOVA found significant main effects for viewing distance, $F(2, 16) = 21.1$, $p < .01$ and motion information, $F(2, 16) = 24.5$, $p < .01$, and a significant interaction, $F(4, 32) = 3.38$, $p < .05$. At the closest distance, accuracy with speed information alone was lower than accuracy with either size information alone, $F(1, 8) = 19.2$, $p < .01$, or with both size and speed information, $F(1, 8) = 62.7$, $p < .01$. Accuracy declined with increasing viewing distance when only size information was available, $F(2, 16) = 10.8$, $p < .01$. Accuracy with speed information did not vary significantly with viewing distance, $F(2, 16) = 0.50$, $p > .05$. At the greatest viewing distance, accuracy with both size and speed information was higher than accuracy with either size information alone, $F(1, 8) = 9.06$, $p < .05$, or speed information alone, $F(1, 8) = 11.4$, $p < .05$.

The results from Experiments 1a and 1b were consistent. When there was only speed information available, accuracy was at near chance levels for all simulated distances. At the nearest distance, accuracy with size information alone was higher than with speed information alone. At the greatest distance, accuracy with size information alone decreased to near chance levels. Figures 7a and 7b show the angular size changes and speed changes of the sphere moving in the most curved trajectory at different distances. As noted earlier, the relation between angular size and distance is a function of perspective and the usefulness of size information is therefore reduced with increased viewing distance. Speed information, on the other hand, has both a perspective and non-perspective component and provides potential information for relative curvature judgments even at great viewing distances.

At the far distance, accuracy with either size information alone or speed information alone dropped to near chance levels, but accuracy remained high when both types of information were available. This indicates that even when speed information does not provide a high level of accuracy in isolation, the availability of speed information together with size information can result in increased accuracy with increased distance.

Experiment 2a—Speed information from perspective and parallel projections: Convex curvatures

Angular speed information can indicate that a motion trajectory is curved in depth in both perspective and parallel projections, although the sign of curvature is available only in perspective projections (Braunstein, 1966). Figure 8 shows how variations in angular speed occur in a parallel projection of an object moving along a circular arc at a constant 3D rotational velocity. In Experiment 1 we found more accurate judgments at greater distances with displays for which the curvature magnitude was indicated by both angular speed and angular size than for displays with size information alone or with speed information alone. The present experiment considers whether speed information that is not related to viewing distance, when presented with size information that is related to viewing distance, can also increase the accuracy of judgments of relative curvature magnitude.

Method

Stimuli—The stimuli in Experiment 2 were similar to those in Experiment 1. All of the conditions in Experiment 1 were included and three additional conditions were added. In the new conditions size information for each viewing distance was presented with speed information from a parallel projection.

Observers—The observers were 12 undergraduate students at the University of California, Irvine, who received course credit for participating. None had participated in other experiments in this study. Each observer had visual acuity of 20/40 or better (Snellen eye chart) in their preferred eye. They were naïve to the purpose of this study.

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

Design—The independent variables were simulated viewing distance (183 cm, 366 cm or 549 cm) and type of motion information. The motion information consisted either of (1) changes in angular size only, (2) changes in angular speed only, (3) changes in both angular size and speed based on the same simulated viewing distance, or (4) changes in angular size based on the 183 cm, 366 cm or 549 cm simulated viewing distance with changes in angular speed based on a parallel projection. The three distances and four types of motion information resulted in 12 conditions. An additional condition was included in which there was no size information for curvature and speed information was based on a parallel projection. There were three types of comparisons for each condition, resulting in 39 trial types. The experiment consisted of 11 blocks of 39 trials with the first block treated as a practice block.

Results and discussion

One observer did not meet the criterion of 70% correct in the near condition with both types of information available. Data from the remaining 11 observers were used in the analysis. Figure 9a shows the accuracy of the relative curvature judgments as a function of the viewing distance and the motion information. A three (viewing distance) by four (type of motion information) ANOVA showed significant main effects for distance, $F(2, 20) = 22.7$, $p < 0.01$, and motion information, $F(3, 30) = 44.9$, $p < 0.01$, and a significant interaction, $F(6, 60) = 3.4$, $p < 0.01$. Accuracy with angular size and speed from parallel projections was higher than accuracy with angular size and angular speed based on the same simulated distance. At the far distance, the accuracy with size and speed from parallel projections was not significantly different from accuracy with both angular size and speed based on the same simulated distance, $F(1, 10) = 1.53$, $p > .05$, but was higher than accuracy with either size information alone, $F(1, 10) = 34.5$, $p < .01$, or speed information alone, $F(1, 10) = 9.69$, $p < .05$. Accuracy in the conditions in which the projected size was constant and speed changes were based on a parallel projection was similar to accuracy in the conditions in which size was constant and speed was based on the simulated viewing distance. These additional conditions in Experiments 2a and 2b were not part of the factorial designs and were not included in the analyses.

Experiment 2b—Speed information from perspective and parallel projections: Concave curvatures

Method

The method was the same as in Experiment 2a except that the sphere moved in a concave arc, first away from the observer and then towards the observer. Sixteen naïve observers from the same population participated. The visual acuity requirement was the same.

Results and Discussion

Five observers did not meet the criterion of 70% correct in the near condition with both types of information available. Data from the remaining 11 observers were used in the analysis. Figure 9b shows accuracy as a function of viewing distance and motion information.

A three (viewing distance) by four (type of motion information) ANOVA showed significant main effects for distance, $F(2, 20) = 37.0$, $p < 0.01$, and motion, $F(3, 30) = 14.1$, $p < 0.01$, as well as a significant interaction, $F(6, 60) = 3.86$, $p < 0.01$. At the far distance, accuracy for all four types of motion information decreased to near chance levels. A one-way ANOVA on type of motion information at the far distance showed no significant differences, $F(3, 30) = 0.46$, $p > .05$.

Accuracy with angular size based on viewing distance and speed from parallel projections was not lower than accuracy with both angular size and speed based on the same simulated viewing distance, for either the convex or concave conditions. This indicates that the speed information from parallel projections is sufficient for increasing the accuracy of judging curvatures in 3D when presented with size information based on perspective projections. We cannot explain why judgments were actually higher with speed information from parallel projections. We can only speculate that the addition of perspective information to the speed functions was in some way a distraction that slightly reduced accuracy. The reduced accuracy in the concave condition at the far distance may be related to a preference for perceiving convex trajectories, similar to the bias that has been found for perceiving convex shapes (e.g., Langer & Bülthoff, 2000).

Experiment 3a—Curvature discrimination with intermediate size and speed values: Convex curvatures

In Experiment 1 we found that the combination of size and speed information resulted in greater accuracy than size information alone at the greatest simulated distance, although performance was at chance levels with speed information alone. There are two possible explanations. One is that the angular speed changes at the far distance, while not sufficient for discriminating among the three curvatures, were sufficient to indicate that the trajectories were curved. This may have facilitated the use of the size information for discriminating curvature magnitude. The second possibility is that the changes in angular speed provided some quantitative curvature information, and although this information was not sufficient for making accurate discriminations in isolation, it combined with the size information to increase the accuracy of curvature discriminations at the far distance. In this experiment we examined these two possibilities.

Method

Stimuli—The stimuli were similar to those in Experiment 1, except that the curvatures of the sphere's trajectories were changed to accommodate the new conditions. The trajectories

were based on arcs of circles with radii of 27.9, 33 and 62 cm, and the curvatures were therefore 0.036, 0.030 and 0.016 cm⁻¹. The three curvatures were labeled 1, 2 and 3, 1 being the least curved and 3 the most curved. Other stimulus parameters were the same as in Experiment 1.

Observers—Fourteen naïve observers from the same population participated. They met the same visual acuity requirement and received extra credit for their participation.

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

Design—The independent variables were simulated viewing distance and type of motion information. Table 1 lists the five types of motion information.

Unlike Experiment 1, the discrimination required on each trial was always between curvature 1 and 3. Size (or speed) information can be considered relevant to the discrimination if the size (or speed) function is different for the displays in a pair that the observer is asked to discriminate. Size (or speed) information can be considered irrelevant to the discrimination if the size (or speed function) is the same in the two displays is a pair. Even if size or speed information is irrelevant to the discrimination, that information may increase accuracy in other ways. For example, size and speed information irrelevant to the discrimination could indicate that both trajectories are curved, facilitating use of the relevant source of information for discriminating between the two curvatures.

The first three types of motion information (size and speed relevant; size relevant, speed constant; and speed relevant, size constant) were the same as in Experiment 1. The fourth and fifth types of motion information are similar to the second and third types, except that instead of size or speed being made irrelevant to the discrimination by simulating linear motion perpendicular to the line of sight, size or speed was made irrelevant by simulating a trajectory curvature intermediate between the two curvatures being discriminated.

There were 15 blocks of 30 trials in the experiment, with a two-minute rest period between blocks. The first block was for practice and was not used in the data analysis. For each display, a modulation (Runeson, 1974) to the speed of the motion was applied to avoid a sudden start of the motion.

Results and discussion

Three observers did not meet a criterion of 70% correct in the near distance, maximum curvature condition with corresponding size and speed information. Data from the remaining eleven observers were used in the analysis. Figure 10a shows the accuracy of the relative curvature judgments for each condition. A three (viewing distance) by five (type of motion information) ANOVA showed significant main effects for distance, $F(2, 20) = 32.2$, $p < 0.01$, and motion information, $F(4, 40) = 16.4$, $p < 0.01$, and a significant interaction, $F(8, 80) = 3.45$, $p < 0.01$. Accuracy with relevant changes in both angular size and speed (condition 1) was greater than accuracy with relevant changes in angular size and changes in speed based on an intermediate curvature (condition 4), $F(2, 20) = 9.07$, $p < 0.05$. Accuracy with relevant changes in angular size and speed based on an intermediate curvature (condition 4) was greater than accuracy with relevant changes in angular size and constant angular speed (condition 2), $F(2, 20) = 31.1$, $p < 0.01$.

Accuracy with relevant changes in both angular size and speed (condition 1) was greater than accuracy with relevant changes in angular speed and angular size based on an intermediate curvature (condition 5), $F(1, 10) = 32.3$, $p < 0.01$. Accuracy with relevant

changes in angular speed and angular size based on an intermediate curvature (condition 5) was greater than accuracy with relevant changes in angular speed and constant angular size (condition 3), $F(1, 10) = 15.5$, $p < 0.01$. These results suggest that speed information contributes to the accuracy of curvature magnitude discriminations in two ways. First, speed information indicating that the paths are curved rather than linear facilitates the use of size information to discriminate which path is more curved. The evidence for this is that accuracy is greater with speed information indicating a curvature intermediate between the two curvatures indicated by size information, compared to displays in which the object is moving at a constant angular speed. This intermediate speed information cannot contribute directly to the accuracy of the judgments. Second, speed information indicating the same curvatures as the size information contributes directly to the accuracy of the discriminations. The evidence for this is that accuracy is greater with speed information that is relevant to the discrimination than with speed information that indicates curvature, but is not relevant to the discrimination because it indicates the same intermediate curvature for both displays in a pair.

Experiment 3b— Curvature discrimination with intermediate size and speed values: Concave curvatures

Method

The method was the same as in Experiment 3a except that the sphere moved in a concave arc. Fourteen naïve observers from the same population participated. All met the same visual acuity requirement and received extra credit for participating.

Results and discussion

Three observers did not meet a criterion of 70% correct in the near distance, maximum curvature condition with corresponding size and speed information. Data from the remaining eleven observers were used in the analysis. A three (viewing distance) by five (type of motion information) ANOVA showed significant main effects for distance, $F(2, 20) = 19.0$, $p < 0.01$, and motion information, $F(4, 40) = 24.5$, $p < 0.01$, and a significant interaction, $F(8, 80) = 5.2$, $p < 0.01$. The differences between accuracy with relevant changes in angular size and speed (condition 1), relevant changes in angular size with speed based on an intermediate curvature (condition 4) and relevant changes in angular size with constant speed (condition 2) were not significant, $F(2, 20) = 1.67$, $p > 0.05$. Accuracy with relevant changes in angular size and speed (condition 1) was greater than accuracy with size based on an intermediate curvature (condition 5), $F(1, 10) = 43.9$, $p < 0.01$, or constant angular size (condition 3), $F(1, 10) = 67.3$, $p < 0.01$. The smaller effects found with concave trajectories probably reflect the generally lower accuracy found with these trajectories.

Experiment 4: Judging sign of curvature

In Experiment 1 we found that speed information presented with size information resulted in increased accuracy of judgments of the relative curvature magnitude of motion trajectories. In this experiment we examined whether displays with both size and speed information would provide more accurate judgments of the sign of curvature than displays with only one type of information available.

Method

Stimuli—The stimuli differed from those in Experiments 1 and 2 in the following way. In Experiments 1 and 2 both displays in a pair were based on the same direction of curvature but differed in the magnitude of curvature. In the present experiment both displays were based on the same magnitude of curvature but differed in the sign of curvature. That is, the

sphere moved in a convex trajectory in one display and moved in a concave trajectory in the other. The order of presentation was counterbalanced. The simulated viewing distance and type of motion information was the same for both displays on each trial.

Apparatus and procedure—The apparatus was the same as in the previous experiments. Half of the observers were asked to indicate which of the two displays in a pair showed a convex trajectory and half were asked to indicate which display showed a concave trajectory. The types of trajectories were explained in terms of the "ball" moving away and then closer or closer and then away from the observer.

Observers—The twelve observers were undergraduate students at the University of California, Irvine who received credit for participating. None had participated in any other experiment in this study. All had visual acuity (corrected if required) of 20/40 or better (Snellen Eye Chart) and were naïve to the purpose of the study.

Design—The independent variables were the simulated viewing distance (183 cm, 366 cm or 549 cm), type of motion information (changes in angular size only, changes in angular speed only and changes in both types of motion information) and curvature magnitude (.036, .027 or .0024 cm⁻¹). As in Experiment 1, there were 11 blocks of 27 trials with the first block treated as a practice block.

Results and discussion

All observers met the criterion of 70% accuracy in discriminating between concave and convex trajectories with the greatest curvature, closest distance and both types of information available. Figure 11a shows the accuracy of judgments averaged across the three levels of curvature magnitude. A three (simulated viewing distance) by three (motion information) by three (curvature magnitude) repeated measures ANOVA showed significant main effects for viewing distance, $F(2, 22) = 29.8$, $p < .01$, motion information, $F(2, 22) = 31.4$, $p < .01$, and curvature, $F(2, 22) = 47.9$, $p < .01$. There were two significant interactions: distance by curvature, $F(4, 44) = 3.00$, $p < .05$, and motion information by curvature, $F(4, 44) = 12.2$, $p < .01$. Accuracy with speed information alone was at near chance levels at all distances, indicating that speed information alone is not sufficient to discriminate convex from concave trajectories of the type studied. Averaged over the three curvature levels, accuracy with both size and speed information was not significantly different from accuracy with size information alone, $F(1, 11) = 1.76$, $p > .05$. This difference was significant for the highest curvature level, $F(1, 11) = 10.4$, $p < .01$. Accuracy of the sign of curvature judgments for trajectories with the highest curvature is shown in Figure 11b.

Although accuracy with speed information alone was at chance levels, angular speed was potentially informative about sign of curvature and could have contributed to accuracy when combined with size information. To further examine the role of speed information, the next experiment used speed functions based on parallel projections which carry no information about sign of curvature for the trajectories studied.

Experiment 5: Judging sign of curvature with speed information from parallel projections

Experiments 1–3 found increased accuracy for relative curvature magnitude judgments for displays with both angular size and speed information at the greatest simulated distance. Experiment 2 showed that speed information from parallel projections increased the accuracy of curvature magnitude judgments when presented with size information. But even in parallel projections there is speed information that may be relevant to judgments of

relative curvature. There is no information in parallel projections, however, for judging sign of curvature. The speed information in parallel projections is identical for concave and convex trajectories. The present experiment investigated whether speed information from a parallel projection, when presented with size information from a perspective projection, can enhance judgments of the sign of curvature for trajectories in a horizontal plane at eye level.

Method

Design and procedure—The design and procedure were the same as in Experiment 4, except that in the combined size and speed information condition the speed information was based on parallel projections rather than based on the same simulated viewing distances as the size information. There were thus three types of motion information: angular size information based on the three simulated viewing distances (183 cm, 366 cm or 549 cm) with angular speed constant, angular speed information based on the same three simulated viewing distances with angular size constant, and angular size information based on the three viewing distances combined with speed information based on parallel projections.

Observers—Ten observers participated in the experiments. They were undergraduates students from UCI and received credit for the participating. All observers had visual acuity (corrected if required) of at least 20/40 (Snellen Eye Chart) and were naïve about the purpose of the experiment. None had participated in any other experiments in this study.

Results and discussion

All of the observers met the accuracy criterion for the near distance with both types of information available. Figure 12a shows accuracy averaged across the three levels of curvature magnitude. A three (simulated viewing distance) by three (motion information) by three (curvature) repeated measures ANOVA showed significant main effects for viewing distance, $F(2, 18) = 12.6$, $p < .01$, motion information, $F(2, 18) = 44.2$, $p < .01$, and curvature, $F(2, 18) = 49.4$, $p < .01$. There were two significant interactions: distance by motion information, $F(4, 36) = 2.87$, $p < 0.05$, and motion information by curvature, $F(4, 36) = 15.1$, $p < .05$. At the far distance, accuracy with size information indicating sign of curvature and speed information based on parallel projections was significantly higher than accuracy with either size information alone, $F(1, 9) = 17.7$, $p < .01$, or speed information alone, $F(1, 9) = 13.0$, $p < .01$. Figure 12b shows the accuracy for the pairs with the most curved trajectories. At the far distance, accuracy with both size and speed information was significantly higher than accuracy with either size information alone, $F(1, 9) = 12.2$, $p < .01$, or speed information alone, $F(1, 9) = 48.0$, $p < .01$.

For all the stimulus pairs in which size and speed information was combined, the speed information was based on a parallel projection and was the same for the convex and concave displays. This means that the speed information that was presented together with the size information could not be used to discriminate between convex and concave displays. The results, however, show that sign of curvature judgments, for the greatest simulated viewing distance, were more accurate when both size and speed information were present than when size information alone was present.

General discussion

Overall, we found greater accuracy when curvature was indicated by changes in angular size only than when curvature was indicated by changes in angular speed only, both for judgments of relative curvature magnitude and judgments of sign of curvature. At the shortest simulated viewing distances (highest perspective level), accuracy with curvature indicated by changes in angular size only was similar to accuracy with curvature indicated

by changes in both angular size and angular speed. Accuracy with changes in angular speed only was near chance levels at all simulated viewing distances.

Although we found high accuracy at near distances with variations in angular size indicating curvature and angular speed constant, we found near chance performance with variations in angular speed indicating curvature and angular size constant. This result is consistent with two previous studies (Todd, 1981; Gray & Regan, 1999). Todd (1981) asked observers to judge where a free-falling projectile would hit the ground. The projectile was represented either by a single dot that did not change in size (motion information only) or a configuration of dots that changed in size in the projection (corresponding motion and size information). Observers were unable to make correct judgments based on motion information only. Gray and Regan (1999), had observers estimate the time-to-collision for patterns of circular dots approaching along the line of sight. The angular size of the dots was held constant during the motion. When the angular size of the dots was large enough (exceeding 2.2–4.4 min of arc), time-to-collision was overestimated, suggesting that the constant dot size conflicted with the motion in depth information. Although the types of motion were different in those two studies and in our study, the results of all three studies indicate that for an object moving in 3D, observers are not accurate in judging object motion from speed information when the moving object maintains a constant angular size.

There are two explanations that might account for the near-chance judgments of curvature magnitude and sign of curvature when only speed information is presented. First, although observers are able to use first-order motion information (speed) for recovering depth in 3D displays, they have limited sensitivity to second-order motion information (acceleration) for recovering depth (Todd & Bressan, 1990; Hogervorst & Eagle, 2000). It is second-order motion information that would be most relevant to judgments of curvature magnitude or sign of curvature. Although observers might have compared speeds at different positions along the trajectories to estimate changes in speed, they could not have used maximum or minimum speeds to compare curvatures between displays in the present study because the initial speed was randomly selected for each display.

A second explanation for the finding of near-chance accuracy with speed information alone is that the interpretation of a change in speed as resulting from a change in depth requires a perceptual constraint of constant 3D speed. Without this constraint, the displays could be interpreted as motion along a straight path with varying 3D speed. On the other hand, size information alone does provide high accuracy at the closer distances. This is likely to be the result of a strong constant size constraint, with changes in the angular size of an object interpreted as changes in its position in depth (Johansson, 1964; Sedgwick, 1986). At the greatest distance, due to reduced perspective effects, size changes were relatively small. The observer may have some tolerance for small changes in angular size and may not interpret small changes in angular size as resulting from changes in depth. This may account for the near chance performance with size information alone at the far distance.

Our finding of higher accuracy at the greatest viewing distance with the speed function indicating a curved trajectory than with the speed constant, and thus indicating a linear trajectory (Experiments 3 and 5), is consistent with the second explanation. In these two experiments, size functions relevant to the discrimination were combined with two different speed functions that were not relevant to the discrimination because they were identical for both displays in a pair. Some display pairs in Experiment 3 had constant angular speeds; other pairs had speeds based on the same intermediate curvature. Accuracy with a speed based on an intermediate curvature was higher than with constant speed. Some display pairs in Experiment 5 had constant angular speeds; others had speeds based on parallel projections, which have identical speed functions for convex and concave trajectories with

the same curvature magnitude. Judgments of sign of curvature were more accurate with speed functions based on parallel projections than with constant speeds. The results of these two experiments suggest that speed information indicating that the path is curved in depth facilitates the perception of small changes in angular size as resulting from changes in distance.

The increase in discrimination accuracy when speed information that was not relevant to the discrimination was combined with relevant size information is not easily handled by cue combination theories. In most types of cue combination, as reviewed by Bühlhoff and Mallot (1988), the cues that are combined each provide information relevant to the required judgment. An increase in accuracy of judgments from a cue that is irrelevant to the discrimination, such as a velocity function based on a curvature intermediate to those being discriminated, or based on a parallel projection when the task was to judge sign of curvature, suggest a different type of interaction between sources of information for judging curvature. Motion information indicating that the trajectory is curved, even if irrelevant to the specific discrimination required of the observer, could be regarded as a form of ancillary information (Landy, Maloney, Johnston, & Young, 1995). In different conditions in the present study, the velocity function could be relevant, if it was different for the two displays in a pair being discriminated, or ancillary, if it was not different or not discriminable in the two displays. To handle the present results, a cue combination model would have to allow the same cue to be either relevant to the discrimination or ancillary, for different display pairs.

An alternative explanation can be found in the concept of intrinsic constraints (Domini, Caudek & Tassinari, 2006; Tassinari, Domini & Caudek, 2008). Even with speed information not informative about degree of curvature or sign of curvature, that information could still indicate that the object was moving in a curved rather than in a straight trajectory. The visual system may have been constrained to find an interpretation of the size changes consistent with a curved trajectory, rejecting the alternative perception that the object was changing in size while moving along a straight path. The importance of the combination of angular size and speed information is also consistent with Craig et al.'s (2009) finding that observers use a combination of optical expansion and optical displacement in the prediction of an object's future position.

In any study using 2D projections to study 3D perception, the question can arise as to whether the judgments could have been based directly on 2D variables rather than on a 3D perception. We used random initial sizes and speeds to prevent comparisons based on the maximum size or speed in a pair of displays. In debriefing, 56 of 98 observers indicated a strong 3D impression in most displays, 27 indicated this for some displays and 15 indicated that they did not have a strong 3D impression. Our finding that in some conditions accuracy from either angular size changes alone or angular speed changes alone dropped to near-chance level, but accuracy based on a combination of these two sources of information was notably higher, also seems inconsistent with observers basing their judgments directly on 2D variables.

Overall, in this study we examined the effects of angular size and speed on perceiving the trajectory of a single object moving in 3D. The results demonstrated that (1) speed information alone does not result in accurate judgments of the magnitude or direction of a curved trajectory, (2) accuracy of judgments based on size information alone decreases sharply with increased distance, but (3) displays that include both speed and size information can provide high accuracy at a far distance even when the speed information is not directly relevant to the required judgment.

Acknowledgments

We would like to thank Brianna Phelps and Amy Vu for their assistance with this research and Adriane Seiffert and three anonymous reviewers for helpful comments. This project was supported by a grant from the National Institutes of Health (EY18334) to G. J. Andersen.

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Figure 1.

Angular size and speed functions for convex and concave trajectories. Note that the angular size is constant for a parallel projection (upper and lower left) but angular speed varies over time for both perspective and parallel projections (upper and lower right). The speed function in parallel projections is identical for convex and concave trajectories.

Figure 2.
Top view of two convex trajectories differing in magnitude of curvature (a and b) and a concave trajectory (c) with the same magnitude as curve a.

Figure 3. Superimposed frames from a convex motion sequence with the highest curvature (top), a convex sequence with the lowest curvature (center) and a concave sequence with the highest curvature (bottom).

(a)

(b)

Figure 4.

(a) Top view of the motion trajectories. Upper: convex; lower: concave. (b) The three simulated eye positions relative to the most curved convex motion trajectory. Note that the 2D projection (not the 3D trajectory) was magnified so that the linear extent in the image matched across simulated viewing distances.

Figure 5.

Changes in angular size and speed in Experiment 1a for simulated viewing distances of 183, 266 and 549 cm. The physical distance from the eye to the monitor was 183 cm. The images on the monitor for the two greater viewing distances were magnified to keep them equivalent in overall extent. The size and speeds in these plots are measured at the monitor after the image is magnified.

(a) Convex

(b) Concave

Figure 6. Proportion of correct judgments of relative curvature magnitude in Experiments 1a and 1b. Error bars represent ± 1 standard error.

Figure 7.

The size (a) and speed (b) changes of the sphere moving in the greatest curved trajectory at different distances. Note the large changes in the size function (a) with simulated viewing distance and the relatively small changes in the speed function (b) with distance.

Figure 8.

A parallel projection of an object moving at a constant rotational velocity along a circular arc (top view). Note that the projection is identical for convex and concave trajectories. (See Braunstein, 1976, Appendix.)

(a) Convex

(b) Concave

Figure 9. Proportion of correct judgments of relative curvature magnitude in Experiments 2a and 2b. Error bars represent ± 1 standard error.

(a) Convex

(b) Concave

Figure 10.

Proportion of correct judgments of relative curvature magnitude in Experiments 3a and 3b. Error bars represent ± 1 standard error. In the legend, interm. is short for intermediate, curv. is short for curvature.

(a) Accuracy averaged over all curvatures

(b) Accuracy with the greatest curvature

Figure 11.

Proportion of correct sign of curvature judgments in Experiment 4. Error bars represent ± 1 standard error.

(a) Accuracy averaged over all curvatures

(b) Accuracy with the greatest curvature

Figure 12.

Proportion of correct sign of curvature judgments in Experiment 5. Error bars represent ± 1 standard error.

Table 1

Types of Motion Information in Experiments 3a and 3b

Condition	angular size	angular speed
1. Size and speed relevant	Based either on curvature 1 or curvature 3	Based on the same curvature as angular size
2. Size relevant, speed constant	Based either on curvature 1 or curvature 3	Constant angular speed (no simulated curvature)
3. Speed relevant, size constant	Constant angular size (no simulated curvature)	Based either on curvature 1 or curvature 3
4. Size relevant, speed based on intermediate curvature	Based either on curvature 1 or curvature 3	Based on curvature 2
5. Speed relevant, size based on intermediate curvature	Based on curvature 2	Based either on curvature 1 or curvature 3