Path Perception during Rotation:

Influence of Instructions, Depth Range, and Dot Density

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Abstract

When traveling on a straight path with eye rotation, how do observers perceive the path of self-motion? Our previous findings suggest that either information from retinal flow alone (such as dense motion parallax and reference objects) or extra-retinal information about eye movements is sufficient for solving this problem for both perceiving and active steering of self-motion (Li & Warren, Vis Res 2000;40:3873-3894; Psych Sci 2002;13:485-491). In this paper, using displays depicting translation with simulated eye rotation, we investigated how task variables such as instructions influenced the visual system's reliance on retinal vs. extra-retinal information for path perception during rotation. Furthermore, we examined whether varying depth range and dot density in random-dot displays influenced the perceived path. We found that path errors were small when observers were instructed to expect traveling on a straight path (consistent with retinal information) or were not informed of the shape of the path, but increased markedly when were instructed to expect traveling on a curved path (consistent with extra-retinal information). Increasing depth range or dot density did not improve performance. We conclude that the expectation that one is on a straight or curved path can push the visual system toward a straighter or more curved interpretation of the ambiguous retinal velocity field for path perception during rotation.

Introduction

Accurate perception of the direction of self-motion, or heading, is important for successful locomotion in the world. Pervious studies have shown that when traveling on a straight path with no eye, head or body rotation, people can accurately judge their heading from the radial pattern of optic flow, which contains a focus of expansion (FOE) in the heading direction (Gibson, 1950; Warren, in press; Warren, Morris, & Kalish, 1988). This is even the case for visually impaired patients with a field of view as narrow as 5? (Li, Peli, & Warren, 2002). However, the perception of heading becomes more complicated when the observer is rotating his/her eye while traveling on a straight path. The eye rotation adds a rotational component to the flow, which alters the radial pattern, eliminates the FOE in the observer's heading direction, and creates a spurious focus at the fixation point. Formal analyses have shown that the instantaneous retinal velocity field is now equivalent to that of traveling on a curved path (Royden, 1994).

In this article we pursue the question of how people perceive heading during eye rotation. Some previous psychophysical results support the view that heading can be recovered from the retinal flow alone because the components due to translation and rotation have different properties (Stone & Perrone, 1997; van den Berg, 1992; van den Berg & Brenner, 1994; Wang & Cutting, 1999; Warren & Hannon, 1988, 1990). Specifically, *motion parallax* between elements at different depths corresponds to observer translation (Rieger & Lawton, 1985), whereas common *lamellar motion* across the visual field corresponds to observer rotation (Koenderink & van Doorn, 1987; Perrone, 1992). However, other results support the view that extra-retinal information about eye movements is necessary to compensate for the rotation, especially at high rotation rates (>1?/s) (Banks, Ehrlich, Backus, & Crowell, 1996; Ehrlich, Beck, Crowell, Freeman, & Banks, 1998; Royden, Banks, & Crowell, 1992; Royden, Crowell, & Banks, 1994).

One drawback to these studies is that they used random-dot displays, which place inherent restrictions on dot density and depth range, and did not contain environmental objects. Both dot density and depth range limit the motion parallax available in the display, and the depth range limits static depth information that could be used to help estimate the rotation (van den Berg & Brenner, 1994a,b). We recently found that observers are more accurate in both judging and actively controlling their path of self-motion with dense textured-mapped displays that include reference objects (Li & Warren, 2000, 2002; see also Cutting, Vishton, Fluckiger, Baumberger, & Gerndt, 1997). We proposed that the visual system recovers the instantaneous heading in the *retinal coordinate system* on the basis of dense motion parallax, and recovers the path in the *world coordinate system* by updating heading with respect to reference objects in the scene. This is consistent with previous analyses showing that, while information in a single velocity field specifies the instantaneous retino-centric heading unambiguously, information must be integrated over time to distinguish various possible paths in the world (Stone & Perrone, 1997; Warren et al., 1991). We thus demonstrated that retinal flow alone is sufficient for path perception during rotation; extra-retinal information also contributes but is not necessary (see also Crowell & Andersen, 2001; Grigio & Lappe, 1999).

It is important to recognize that, in all of these experiments, there is a cue conflict between retinal and extra-retinal information during simulated rotation. As noted above, the retinal velocity field for traveling on a straight path with eye rotation is equivalent to that for traveling on a curved path, with the curvature of the path defined by the ratio between the instantaneous translation speed and the eye rotation rate (Royden, 1994). In simulated rotation displays, the flow pattern on the screen simulates the effect of forward translation plus an eye rotation, but the eye actually remains stationary. Thus, any extra-retinal signals would indicate zero eye rotation. If the visual system relies on an extra-retinal signal, the rotational component in the flow will be attributed to a curved path in the world. On the other hand, the retinal flow specifies that the heading is fixed in the visual environment, yet when one is traveling on a curved path, the heading should shift with respect to objects over time. Thus, if the visual system relies on retinal information, the rotational component in the flow will be attributed to observer rotation and travel on a straight path will be perceived. Such a conflict may account for the many inconsistent results in the heading perception literature. If so, we should be able to push the observer toward a straight or curved path percept by manipulating the information and the task.

We previously showed that, with texture-mapped displays that contain dense parallax and reference objects, observers can judge their path with an accuracy of a few degrees despite conflicting extra-retinal signals (Li & Warren, 2000). In the present experiments, we investigated how task variables such as instructions influenced observers’ path judgments. Specifically, using displays with simulated eye rotation, we told observers that they were traveling on a straight path (consistent with retinal information), a curved path (consistent with extra-retinal information), or did not mention the shape of the path. In addition, we examined whether varying depth range and dot density in random-dot displays influenced observers’ performance. The depth range and dot density affect the static depth and motion parallax information available in the display. We found that for both texture-mapped and random-dot displays, path errors were small when observers were not informed of the shape of the path. Observers given straight and curved path instructions had large differences in performance and actually thought they were viewing two different classes of displays. Increasing depth range in random-dot displays reduced path errors only with curved path instructions, and there were no effects of dot density. The results lead us to propose that, under cue conflict conditions such as translation with simulated eye rotation, the expectation that one is on a straight or curved path can push the visual system toward a straighter or more curved interpretation of the ambiguous retinal velocity field.

General Method

Display

Displays were similar to those of Li & Warren (2000). They depicted the flow pattern for an observer traveling over a ground plane on a straight path at a fast walking speed of 2 m/s with an eye height of 1.6 m, while fixating to one side. The path direction was varied along a horizontal axis and the observer's task was to position a probe on the perceived future path at the end of each 1.5 s trial. The fixation point was a red circle attached to a post in the scene at eye level; it only moved horizontally and thus eye rotation was about the vertical axis. The effect of eye rotation on the flow pattern was simulated in the display, while the fixation point remained stationary on the screen. Any extra-retinal information thus corresponded to zero eye rotation, although the display simulated both translation and rotation. The mean rotation rate[1] was specified for a given trial (0, ±3, or ±5?/s). Positive values are to the right of center screen, negative values to the left. Final fixation angles were chosen at each mean rotation rate so that the final angle did not co-vary with the mean rotation rate. This resulted in the fixation point distance varying from 6 to 13 m from trial to trial.

The displays were generated on a Silicon Graphics Crimson Reality Engine at a frame rate of 30 Hz, and were rear-projected on a large screen (112? H x 95? V) with a Barco 800 graphics projector with a 60 Hz refresh rate. Observers viewed the screen monocularly from a chin rest using their preferred eye. The chin rest was placed at a distance of 1 m, positioned at the display's center of projection at a height of 1.6 m. The edges of the screen were in the periphery against a black background in a dark room, minimizing the possibility that they might provide a stationary frame of reference.

Procedure

On each trial, the first frame appeared for 1 s to allow observers to fixate the fixation point, followed by 1.5 s of motion. The motion then stopped, the last frame remained visible, and a blue probe line (9.1? tall) appeared on the ground at a distance of 10 m. The azimuth position of the probe could be adjusted along an arc with a 10 m radius using the mouse. Observers were instructed to track the fixation point throughout the trial and, at the end of the trial, to position the probe on their perceived future path, assuming they continued to travel on their present path. The probe and the last frame remained visible until they clicked a mouse button, which started the next trial. To make

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[1] Mean rotation rate is determined by the average of the instantaneous rotation rate over the duration of a trial (see Li & Warren, 2000).

sure observers understood the task and the response device, they received a set of practice trials before each condition. No feedback was provided on any trial. An experimental session typically lasted less than an hour.

Experiment 1

The purpose of the first experiment was to investigate whether instructions about the shape of the path can bias the observer's interpretation of the ambiguous velocity field during simulated rotation. We used three sets of instructions: observers were told they were traveling on a *Straight* path, a *Curved* path, or else the shape of the path was not mentioned (*Neutral*). Two display conditions were tested: the *Textured Ground* (Figure 1a) provided a dense local motion parallax and one reference object (the fixation post), whereas *Dense Posts* (Figure 1b) contained motion parallax among objects, edge parallax, and multiple reference objects. We previously found that both of these displays allowed accurate path judgments under simulated rotation with neutral instructions, despite conflicting extra-retinal signals (Li & Warren, 2000).

The Straight path instructions are consistent with the retinal information for translation with simulated eye rotation, so if they can bias the visual system to rely on retinal information about the current path, we would expect small errors. Conversely, the Curved path instructions are consistent with the extra-retinal signals for zero eye rotation. Hence, if they can bias the visual system to rely on extra-retinal information, we would expect observers to perceive curved paths of self-motion, and thus the path error should increase markedly with rotation rate.

Insert Figure 1 about here

Method

Participants. Ten students and staff at Brown University were paid to participate, all with normal or corrected-to-normal vision. Among them, four were experienced subjects and the rest were participating in a path perception experiment for the first time. We observed no systematic performance differences between the experienced and the naïve observers.

Displays. The simulated mean eye rotation rates were 0, ?3, ?5?/s. As a control, we tested mean rotation rates of ?5?/s in an *Actual Rotation* condition in which the fixation point moved horizontally on the screen and observers tracked its motion with a pursuit eye movement. Any extra-retinal information thus corresponded to the actual eye rotation and agreed with the retinal information in the display. The mean rotation rates were crossed with two display conditions. (1) *Textured Ground* (Figure 1a): The ground plane (240 m wide x 120 m deep) was texture-mapped and the sky was black. The texture map was composed of a filtered noise pattern with a power spectrum of $1/f^2$ for the range of frequencies from 8 to 32 cycles across the image. The image was anti-aliased with a mipmap-bilinear minification filter. A red fixation point appeared at the top of a white post that was anchored to the ground, providing a reference object in the display. (2) *Dense Posts* (Figure 1b): The ground plane was a flat green (240 m wide x 120 m deep), with 231 granite-textured posts positioned in 7 rows of 33 posts each, spanning a depth range of 1-18 m. The distance of posts between rows varied randomly from 1.5 to 4.5 m, and the distance between posts within a row varied randomly from 0.4

to 1.2 m, with a density of about 0.5 posts/m^2. Each post was 0.11 m wide, varied randomly in height between 2-3 m, and was randomly rotated out of the frontal plane from –35° to +35° about its vertical axis. A red fixation point was attached to one of the posts.

Instructions. Three sets of instructions were tested. (1) *Straight path:* Observers were told that the display depicted their walking on a straight path while looking at an object off to one side. (2) *Curved path:* Observers were told that the display simulated their walking on a curved path while looking at an object off to one side. (3) *Neutral:* The shape of the path was not mentioned. Observers were told that the display depicted their traveling on a path while looking at an object off to one side.

Procedure. Trials were presented in two test sessions, one for each display type. In each session, the three instruction conditions and the Actual Rotation condition were tested in a random order, with 10 practice trials before each instruction condition. In the Actual Rotation condition, the Neutral instructions were used. Subjects participated in both test sessions in a counterbalanced order, about one day apart. There were 105 trials (21 trials for each eye rotation rate) in each instruction condition and 42 trials in the Actual Rotation condition, for a total of 377 trials in a session. Trials were blocked by testing condition and randomized within blocks.

Results

Mean constant path error for the Textured Ground display is plotted as a function of mean rotation rate in Figure 2a. A flat function indicates that path judgments were unaffected by rotation rate, whereas a positive slope indicates that error increased in the direction of rotation, and a negative slope that error increased in the opposite direction.

The data for the Curved path instructions show large errors in the direction of rotation, up to 12? at 5?/s. This is consistent with the perception of a curved path of self-motion, which observers reported in a debriefing, and the magnitude of the effect is comparable to that of Royden et al. (1992, 1994) for random-dot displays with neutral instructions.

On the other hand, path errors are significantly smaller in the other instruction conditions, remaining below 7? with Neutral instructions, and below 4? with Straight path instructions, across all rotation rates. A multivariate regression analysis reveals that slope in the Neutral instruction condition (1.29) is reliably shallower than that in the Curved instruction condition (2.19), $t(162)=3.16$, $p<.01$. There are indications that the Straight path instructions may reduce errors further, for the slope (0.76) is marginally shallower than that for Neutral instructions, $t(162)=1.87$, $p=.062$. However, the slope in the Straight instruction condition is still greater than that in that Actual Rotation condition (-0.33), $t(162)=3.52$, $p<.001$, which is not significantly different from zero, $t(36)=-1.99$, *ns*, and is thus statistically flat. This confirms the contribution of extra-retinal information in path recovery during rotation. The slopes for both Straight and the Neutral instructions are statistically greater than zero, with $t(96)=4.8$, $p<.0001$ and $t(96)=5.67$, $p<.0001$, respectively.

A similar pattern of results is found with the Dense Posts display (Figure 2b). The slope in the Curved instruction condition (1.74) is significantly greater that that in the Neutral instruction condition (1.06), $t(162)=2.92$, $p<.01$, where mean errors remain below 5? at all rotation rates. Straight path instructions reduce mean errors to below 3?, with a slope (0.58) that is significantly shallower than that for Neutral instructions, $t(162)=2.09$, $p<.05$. In this case, the slope in the Actual Rotation condition is negative (-

0.49) and significantly different from zero, *t*(162)=-2.55, *p*<.05, indicating that some observers may be overestimating the visual angle between the path direction and the fixation direction by a couple of degrees. If this were also true for the Simulated rotation, it would artificially reduce the estimated path errors overall, but would not affect the differences between instruction conditions. Multivariate regression analyses indicate that although the slopes for the Dense Posts displays were shallower than those for the Textured Ground displays, they are not statistically different: for the Curved path instructions, *t*(96)=-1.88, *ns*, for the Neutral instructions, *t*(96)=-0.71, *ns*, and for the Straight Path instructions, *t*(96)=-0.80, *ns*.

In a debriefing immediately following the test session, eight (2 experienced) out of ten subjects reported seeing two different classes of displays for the Straight and the Curved path instruction conditions.

Insert Figure 2 about here

Discussion

First, the results demonstrate that Straight or Curved path instructions can influence observers' interpretation of the retinal flow under cue conflict conditions. For both the Textured Ground and the Dense Posts displays, the Curved path instructions significantly increased path errors, whereas the Straight path instructions significantly improved accuracy. The fact that observers reported seeing different classes of displays in the different instruction conditions indicates that this was not merely a response bias, but reflected their perceptual experience of the displays. We suggest that the instructions may have led observers to resolve the path ambiguity by differentially relying on retinal information that was consistent with a straight path (such as dense motion parallax and reference objects), or on extra-retinal signals for zero eye rotation that were consistent with a curved path.

Second, the results confirm previous findings that both retinal flow and extra-retinal information contribute to recovering the path of self-motion during rotation. With Neutral instructions, mean path errors remain below 7? for the Ground Plane and below 5? for the Dense Posts during simulated rotation, compared with previous errors of 15? at 5?/s for random dot displays (Ehrlich, et al., 1998; Li & Warren, 2001; Royden, et al. 1992, 1994). This replicates our finding that given sufficient retinal information, the visual system depends primarily on retinal flow and can determine the path of self-motion to within a few degrees, even with conflicting extra-retinal signals (Li &Warren, 2000, 2001). Such a pattern of results demonstrates that extra-retinal information is not necessary to recover the path of self-motion with reasonable accuracy. However, more accurate judgments were obtained in the Actual Rotation condition, when extra-retinal signals about eye position were concordant with the retinal information. This result confirms earlier findings that extra-retinal signals can contribute to path perception during eye rotation.

Experiment 2

The previous experiment examined the effect of instructions on the perceived path of self-motion using texture-mapped displays that contained dense motion parallax, a large depth range, and reference objects. In the present experiment, we tested whether instructions similarly help to resolve the path ambiguity in random-dot displays, where observers tend to see a highly curved path of self-motion (Banks et al., 1996; Li & Warren, 2000; Royden, 1994). In addition, we manipulated the visible depth range and the dot density of the ground plane to determine whether these variables influence the perceived path in random-dot displays. As noted above, the depth range and dot density affect the static depth and motion parallax information available in the display.

We used the Straight and the Curved path instructions to manipulate observers' expectations about their path of travel during simulated rotation. If the instructions influence the interpretation of the retinal flow pattern in this cue conflict situation, we would expect more accurate path judgments with Straight than with Curved path instructions across all dot conditions. If increasing the depth range or dot density of the ground plane provides useful static depth or motion parallax information, we would also expect more accurate judgments with greater density and depth.

Method

Subjects. Twenty-six observers were paid to participate, all students or staff at Brown. One did not finish the experiment and two others made large errors in the Actual Rotation condition, so they were removed from the sample. This left 23 total in the final group. Three of them were experienced subjects who participated in Experiment 1 and the rest were naïve. Again, we observed no systematic performance differences between the experienced and the naïve observers.

Displays. Displays depicted a ground plane consisting of green random dots on a black background (see Figure 3). A red fixation point appeared on the top of a white post that was anchored to the ground, providing a reference object in the display. There were three display conditions. (1) *15 m Depth/Low Density:* 1050 green dots were distributed on the ground plane that extended 15 m in depth and 100 m in width from the eye point (Figure 3a). In specific, one dot was positioned in each cell (1.43 m wide x 1 m deep) of a rectangular grid on the ground, and was randomly jittered from the center of the cell on each trial. This resulted in the dot density of 0.7 dots/m^2. Each dot consisted of a 2 x 2 cluster of pixels, and an anti-aliasing routine was used so that the centroid of the cluster moved smoothly over time. (2) *35 m Depth/Low Density:* The depth range of the ground plane was increased to 35 m (Figure 3b). 2450 dots were distributed on the ground to keep the dot density at 0.7 dots/m^2. (3) *35 m Depth/High Density:* Dot density was increased to 2 dots/ m^2, with a depth range of 35 m (Figure 3c). Thus, 7000 dots were distributed on the ground, with one dot positioned in each cell (0.5 m wide x 1 m deep) of the grid.

Insert Figure 3 about here

Procedure. The Curved and the Straight path instructions were crossed with the three display types, yielding six conditions with blocked trials. Eleven naïve and two experienced observers viewed the three types of displays in a counterbalanced order. For each display type, the testing order of the Curved and Straight instructions was counterbalanced, with 10 practice trials before each condition. There were 105 test trials in each condition, for a total of 630 trials in a session. As a control, we ran a separate Actual Rotation condition with the Neutral instructions for the 15 m Depth/Low Density ground display (42 test trials). Nine new naïve and all three experienced observers participated in the Actual Rotation condition.

Results

Mean path errors for the three displays appear in Figure 4. For all display types, the slope for the Curved path instruction condition is significantly larger than that for the Straight path instruction condition. For the 15 m Depth/Low Density ground, the slopes are 3.56 and 1.41 for the Curved and the Straight instructions respectively, $t(126)=7.26$, $p<.0001$ (Figure 4a); for the 35m Depth/Low Density ground, the slopes are 2.75 and 1.37, respectively, $t(126)=4.29$, $p<.0001$ (Figure 4b); and for the 35m Depth/High Density ground, they are 3.13 and 1.33, respectively, $t(126)=5.98$, $p<.0001$ (Figure 4c). This indicates that despite the sparse structure in random-dot displays and conflicting extra-retinal signals, the Straight path instructions can still push observers toward a straighter interpretation of the retinal flow. Separate analyses indicate that the slope for the Straight path instruction condition is significantly different from zero for all three display conditions: for the 15m Depth/Low Density ground, $t(126)=6.69$, $p<.0001$; for the 35m Depth/Low Density ground, $t(126)=5.99$, $p<.0001$; and for the 35m Depth/High Density ground, $t(126)=6.21$, $p<.0001$. On the other hand, the slope for the Actual Rotation condition for the 15m Depth/Low Density ground (-0.40) is not statistically different from zero, $t(80)=-1.77$, *ns*. This pattern of results is consistent with an extra-retinal contribution to the perceived path of self-motion.

With the Curved path instructions, there is a significant effect of depth range: the slope for the 35m Depth/Low Density condition is significantly shallower than for the 15m Depth/Low Density condition, $t(189)=-2.71$, $p<.01$. However, there was no such effect with the Straight path instructions, $t(189)=-0.10$, *ns*. Thus, the depth range of the ground seems to reduce path errors only with the Curved instructions. On the other hand, we observed no effect of dot density: the slope for the 35m Depth/Low Density condition is not statistically different from that for the 35m Depth/High Density condition with either the Curved instructions, $t(189)=1.26$, *ns,* or the Straight instructions, $t(189)=-0.14$, *ns*. Thus, the present manipulation of dot density did not influence observers' path judgments.

We then compared observers' performance for the 35m Depth/High Density ground with that for the texture-mapped displays in Experiment 1. With the Straight path instructions, the slope for the 35m Depth/High Density ground is marginally higher than that for the Textured Ground display ($t(111)=-1.89$, $p=.06$), and is significantly greater than that for the Dense Posts display ($t(111)=-2.71$, $p<.01$). With the Curved path instructions, the slope for the 35m Depth/High Density ground is significantly higher than that for both the Textured Ground, $t(111)=-3.34$, $p<.01$, and the Dense Posts display, $t(111)=-4.94$, $p<.0001$. This indicates that regardless of the path instructions, observers' path performance for our random-dot display that contains the largest depth range and dot density is still not as good as that for the texture-mapped displays.

Insert Figure 4 about here

Discussion

As we found in Experiment 1, the Straight or the Curved path instructions can push observers toward the perception of a straighter or a more curved path during simulated rotation. This appears to be the case for random-dot displays with sparse structure as well as for texture-mapped displays with relatively complex structure. Nevertheless, path judgments remain significantly more accurate with textured-mapped displays, at least with the Straight or the Curved instructions.

In the current experiment, we found that increasing the visible depth range of the ground plane from 15 to 35 m improved path accuracy with the Curved instructions, but not with the Straight instructions. Van den Berg and Brenner (1994) previously reported that increasing the depth range of the ground plane from 12 to 40 m similarly reduced heading errors, consistent with a straighter perceived path of self-motion (but see Ehrlich, et al., 1998). They proposed that static depth cues could help observers identify distant points near the horizon, whose motion is dominated by the rotational component of flow, allowing the visual system to estimate and remove the rotation. With a larger depth range, more distant points provide a more accurate rotation estimate, but the rotation could be attributed to either eye movement or path curvature. Thus, reduced error with the Curved instructions is somewhat paradoxical, because depth cues do not help resolve the path ambiguity. On this hypothesis, we would expect a similar effect with the Straight instructions, which we do not observe. We look for a depth range effect with the Neutral instructions in Experiment 3.

Finally, the data do not support the hypothesis that increasing the dot density in random-dot displays can improve path judgments. Theoretically, a dense motion parallax field would allow the visual system to determine the instantaneous retino-centric heading more accurately, which may be preliminary to recovering the path in the world. It is possible that we did not test a sufficiently high density, given the inherent limits on the density of random-dot displays because of crowding due to linear perspective. In addition, we only varied dot density at one depth range (35 m), and thus would have missed any improvement with density at shorter depth ranges (e.g. 15 m). In Experiment 3, we re-examine the dot density effect at both 15 and 35 m depth ranges, using the Neutral instructions.

Experiment 3

The purpose of this experiment is twofold. First, we investigate whether the effect of an increased depth range on path judgments recurs with the Neutral instructions. Second, we test for an effect of dot density at both 15 m and 35 m depth ranges.

Method

Fourteen Brown students and staff were paid to participate. Two were removed from the sample because they could not understand the instructions and perform the task, leaving 12 in the final group. Among them, three were experienced subjects who had participated in previous experiments; there were no systematic differences in performance between experienced and naïve observers.

Two ground depths (15 and 35 m) were crossed with two dot densities (0.7 and 2 dots/m^2), generating four display conditions: 15 m depth/Low Density display, 15 m depth/High Density display, 35 m depth/Low Density display, and 35 m depth/High Density display. Only the Neutral instructions were tested. Each subject participated in the four display conditions (105 trials per condition) in a counter-balanced order. Ten practice trials were provided before each display condition commenced.

Results

Mean path errors in the four conditions appear in Figure 5. First, the slope for the 35 m ground is not statistically different from that for the 15 m ground at either the Low (0.7 dots/m^2) or the High Density (2 dots/m^2). At the Low Density, the slopes for the 35 m ground and the 15 m ground are 1.29 and 1.55 respectively, $t(116)=.93$, *ns;* at the High Density, the slopes are 1.35 and 1.73, $t(116)=1.44$, *ns*. This indicates that increasing the depth range does not improve path judgments with the Neutral instructions.

Second, the slope for the Low Density condition is not statistically different from that for the High Density condition, at either the 15 m depth range, $t(116)=-0.66$, *ns*, or the 35 m depth range, $t(116)=-0.21$, *ns*. This confirms the finding in Experiment 2 that increasing dot density does not improve path accuracy.

Next, we compared the present slopes with the Neutral instructions to those for the Straight and the Curved instructions in Experiment 2. For the three display conditions tested in both experiments, the Neutral slope is not different from the Straight slope, but it is significantly shallower than the Curved slope. For the 15 m Depth/Low Density display, the comparisons were $t(184)=.49$, *ns*, and $t(184)=6.88$, $p<.0001$, respectively (Figure 4a); for the 30 m Depth/Low Density display, they were $t(184)=-.27$, *ns*, and $t(184)=4.66$, $p<.0001$, respectively (Figure 4b); and for the 30 m Depth/High Density display, they were $t(184)=.06$, *ns*, and $t(184)=6.13$, $p<.0001$, respectively (Figure 4c). This indicates that for random-dot displays with simulated eye rotation, observers perform the same with the Neutral instructions as they do with the Straight instructions, whereas the Curved instructions push observers toward a more curved interpretation of the retinal flow.

Finally, we compared observers' performance on the present random-dot displays to that on the Textured Ground display in Experiment 1, with the Neutral instructions. Multivariate regression analyses do not reveal any statistical differences in slope: for the 15 m depth/Low Density display, *t*(106)=-0.79, *ns*; for the 15 m depth/High Density display, *t*(106)=-1.35, *ns*; for the 35 m depth/Low Density display, *t*(106)=.03, *ns*; and for the 35 m depth/High Density display, *t*(106)=-.15, *ns*. These results indicate that path judgments with the random-dot ground are comparable to those with the texture-mapped ground.

Insert Figure 5 about here

Discussion

The present experiment revealed no effects of depth range or dot density on path judgments during simulated rotation, using the Neutral instructions. In addition, accuracy with the Neutral instructions was comparable to that with the Straight path instructions in Experiment 2, and performance on the present random-dot ground was comparable to that on the texture-mapped ground in Experiment 1, with the Neutral instructions. We consider these results in turn.

In contrast to van den Berg and Brenner (1994), we find that increasing the visible depth range of a random dot ground does not improve path judgments, using the Neutral instructions. There is thus little indication that the visual system relies on distant points to estimate and remove the rotational component of flow. One important difference between the two studies is that van den Berg and Brenner used a fixation point lying on the ground, whereas we used one on a post at eye level. Banks et al. (1996) pointed out that a fixation point on the ground plane provides a special horizon cue that observers could use to estimate heading during simulated rotation. In this case, the retinal flow pattern spirals outward from the fixation point, with a unique strip of flow vectors that are aligned in the same direction. The intersection of this strip with the horizon corresponds to the current heading point. As the depth range of the ground plane is decreased, the intersection point shifts in the direction of rotation, which could have led to increased errors with a short depth range in van den Berg & Brenner's (1994) study. We eliminated the horizon cue by using a fixation point at eye level, and this could account for the absence of a depth range effect in the present experiment. On the other hand, it is also possible that a greater variation in the depth range could yield a measurable effect.

Second, increasing dot density from 0.7 to 2 dots/m^2 does not improve path judgments at either the 15 m or the 35 m depth range, confirming the results of Experiment 2. We conclude that dot density does not affect the perceived path of self-motion over this density range. This finding seems to be at odds with our earlier proposal (Li & Warren, 2000) that path perception depends on a dense motion parallax field, which offered one reason why path judgments were better with dense texture-mapped displays than sparse random-dot displays. Surprisingly, path errors were relatively small in the present experiment, remaining below 8? at 5?/s even for the 15 m/Low Density display, compared with errors up to 15? at 5?/s for Li and Warren's (2000) random-dot display (20 m depth range, 0.7 dots/m^2). Path accuracy with the random dot ground in the present experiment was actually comparable to that with the textured ground in Experiment 1 (Neutral instructions). Thus, the density of motion parallax cannot account for the improved path judgments with texture-mapped displays. We consider another explanation in the General Discussion.

Finally, we note that the path judgments with the Neutral instructions in this experiment are comparable to those with the Straight instructions in Experiment 2. This suggests that retinal flow information tends to dominate with random-dot displays, even without explicit path instructions.

General Discussion

The present experiments allow us to draw several conclusions. First, we replicated previous findings that both retinal and extra-retinal information contribute to path perception during rotation (Li & Warren, 2000, 2002). In the simulated rotation condition, errors remain below 5? at a rotation rate of 5?/s with the Dense Posts display (Neutral instructions), indicating that retinal flow is sufficient for reasonably accurate path judgments, even when in conflict with extra-retinal signals. On the other hand, accuracy improves further in the actual rotation condition, when extra-retinal signals are congruent with the retinal flow, indicating that they also contribute to path perception (Banks et al., 1996; Royden et al., 1992).

We argue that observers use the retinal motion parallax field to determine their instantaneous retino-centric heading, and recover their path through the world by updating this heading estimate with respect to reference objects in the scene. This yields the observer's object-relative path. Recent evidence suggests that extra-retinal signals may merely serve to indicate whether or not the eye is rotating, thereby gating the interpretation of the rotational component of retinal flow as being due to eye rotation or to a curved path of self-motion (Crowell & Anderson, 2001). With reference objects in the display, these two sources of information are in conflict, yet the object-relative path tends to dominate. This is supported by our finding that performance with the Neutral instructions is closer to that with the Straight path than with the Curved path instructions, and in some cases the two are not significantly different.

Second, we find that instructions can influence the observer's interpretation of the retinal flow pattern under the cue conflict conditions. This is the case for both texture-mapped displays and for random-dot displays. We suggest that straight or curved path instructions lead the visual system to rely more upon retinal information for object-relative heading, which specifies a straight path, or upon extra-retinal signals for zero eye rotation, which indicates a curved path. This would explain why participants believe that they have actually viewed two different classes of displays corresponding to straight and curved paths of self-motion.

Finally, the results indicate that increasing the dot density or depth range of random-dot displays does not improve path judgments during simulated rotation, at least over the ranges tested. Surprisingly, even a low dot density of 0.7 dots/m^2 and the shorter depth range of 15 m yielded relatively accurate path judgments, with errors below 8? at high rotation rates. This indicates that denser motion parallax, yielding more accurate heading estimates, cannot account for the improved performance with texture-mapped displays reported by Li and Warren (2000). Similarly, with the Dense Posts display, there is a comparably low density of motion parallax between posts (0.5 posts/m^2), yet path judgments are the most accurate. In addition, we found no evidence that a more distant horizon (35 m vs. 15 m) contributes to compensating for rotation with either the Straight or the Neutral instructions.

The remaining puzzle is the unexpectedly good performance we observed with random-dot displays (Neutral instructions), which was comparable to that with the Textured Ground display. Path error in Experiment 3 remained below 8? at 5?/s, half of Li and Warren's (2000) error of 15? at 5?/s with a random-dot ground. We believe that the improved accuracy in the present study can be attributed to our large field of view. The present random-dot displays, as well as Li and Warren's (2000) texture-mapped displays, had a large field of view (112? H x 95? V), whereas the random-dot displays of Li and Warren (2000) and previous researchers (Banks, et al., 1996; Ehrlich, et al., 1998), had a field of view less than two-thirds the size (69? H x 59? V). As shown formally by Koenderink & van Doorn (1987), a large field of view improves the estimation of rotation from the retinal flow and increases the magnitude of motion parallax in the peripheral regions of the display. Consistent with this observation, Grigo and Lappe (1999) reported accurate heading judgments with a large frontal plane of dots (90° H x 90° V), whereas previous researchers had found high errors for small displays of a frontal plane (40° H x 32° V, Warren & Hannon, 1990). In the present case, a larger field of view may have allowed the visual system to determine the instantaneous heading more accurately, even at low dot densities. In combination with a reference object (the fixation post), this may have permitted better object-relative path judgments.

In sum, the present results are consistent with Li and Warren's (2000, 2001; Warren, in press) proposal that one's path through the environment can be determined from retinal flow. Specifically, we argue that the instantaneous retino-centric heading is determined from motion parallax between elements at different depths, which is particularly effective over a large field of view. The rotational component is simultaneously determined by detecting the lamellar flow over a large field of view. The path through the world is then recovered by updating the heading with respect to objects in the scene over time. The role of extra-retinal signals is to gate whether the lamellar flow should be attributed to a pursuit eye movement or a curved path of self-motion. During simulated rotation, extra-retinal signals conflict with the retinal flow and reference objects. In this case the latter tend to dominate, with a partial extra-retinal influence, leading to perception of the object-relative path with slight curvature in the direction of rotation. With more objects in the scene, as in the Dense Posts display, the visual frame of reference they provide is more strongly defined and the object-relative path is determined more accurately.

Author Notes

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Figure Captions

Figure 1. Display conditions in Experiment 1. (a) Textured Ground. (b) Dense posts.

Figure 2. Mean path error as a function of rotation rate in Experiment 1. (a) Textured Ground. (b) Dense Posts. Error bars represent between-subjects SEs.

Figure 3. Display conditions in Experiment 2. (a) 15m Depth/Low Density. (b) 35m Depth/Low Density. (c) 35m Depth/High Density.

Figure 4. Mean path error as a function of rotation rate in Experiment 2. (a) 15 m Depth/Low Density. (b) 35m Depth/Low Density. (c) 35m Depth/High Density. Error bars represent between-subjects SEs.

Figure 5. Mean path error as a function of rotation rate in Experiment 3. Error bars represent between-subjects SEs.

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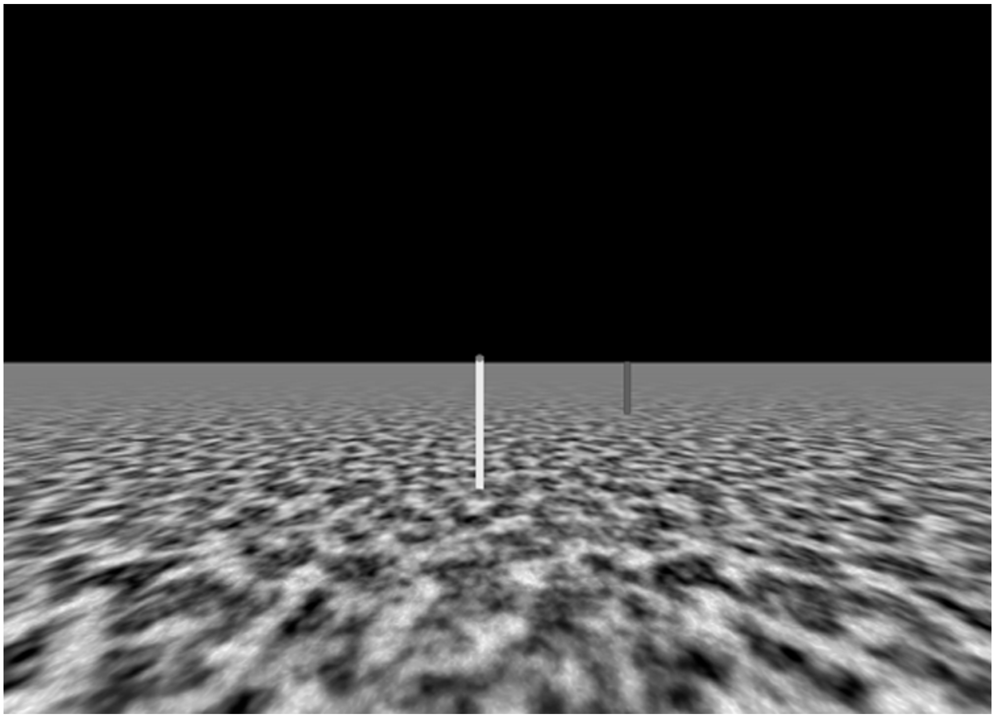
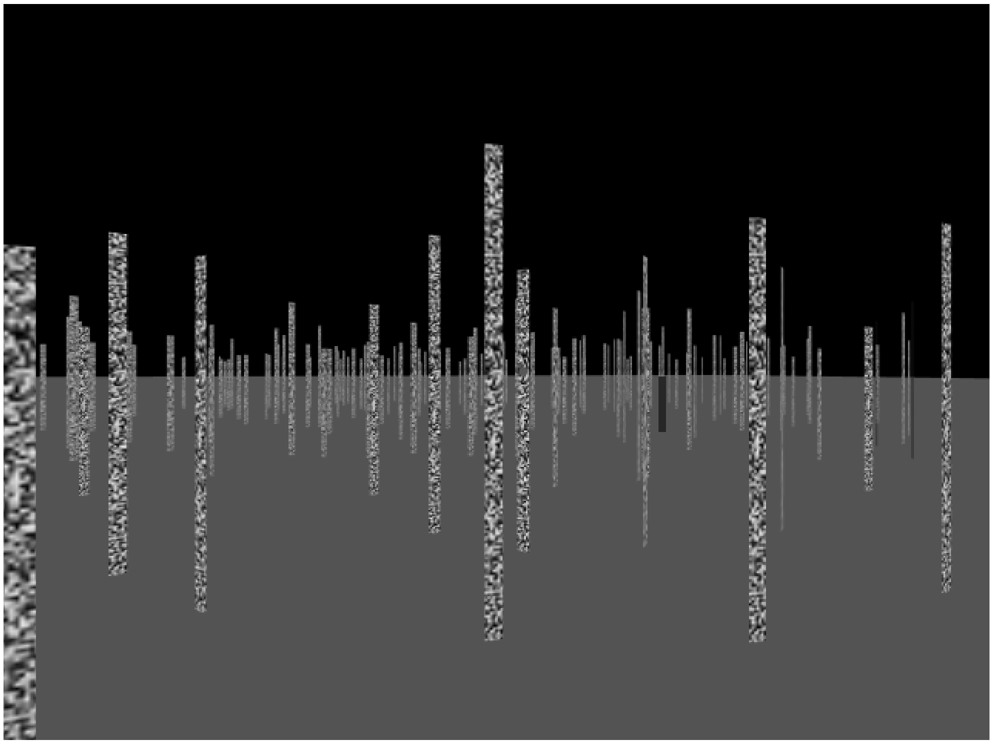
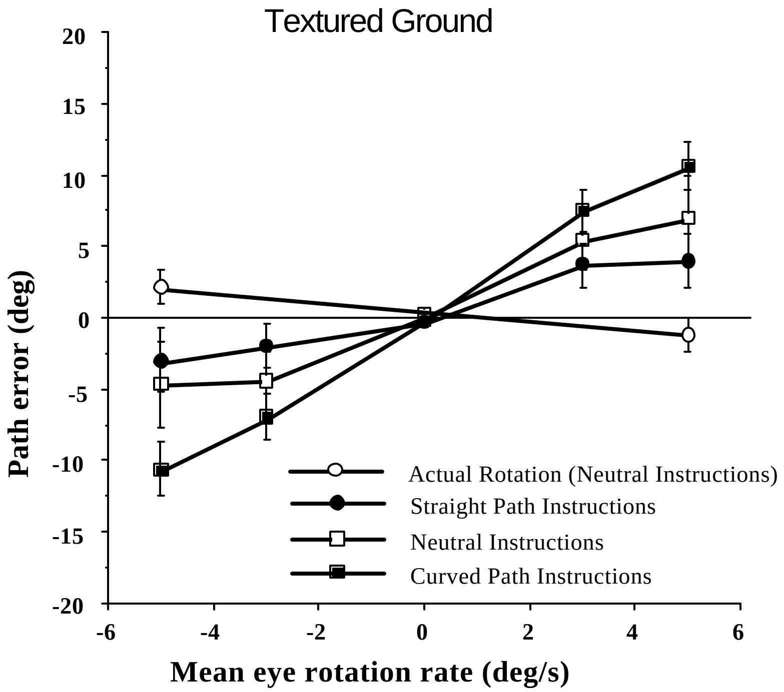


(a)

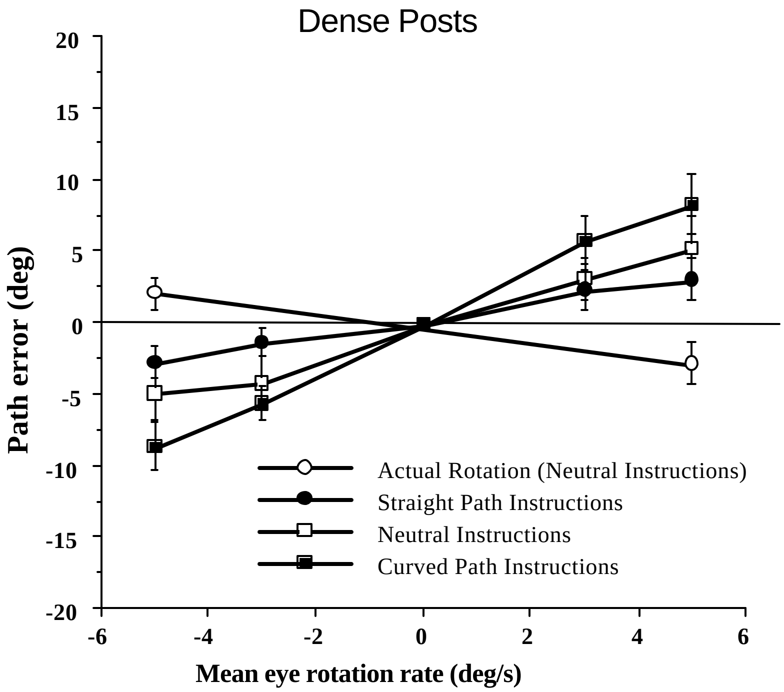


(b)

fig. 1

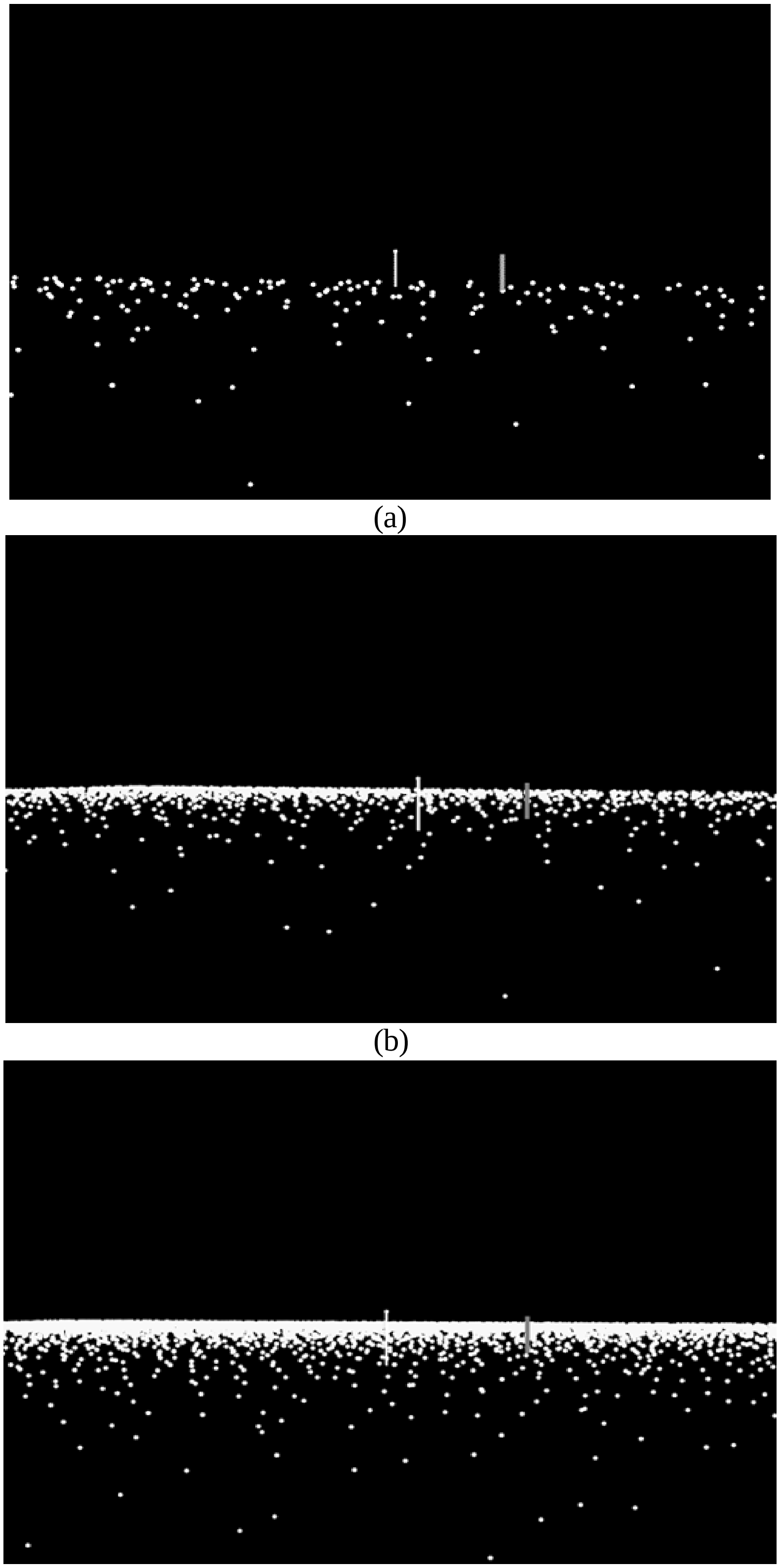

Textured Ground
Path error (deg)
20
15
10
5
0
-5
-10
-15
-20
-6
-4
-2
0
2
4
6
Mean eye rotation rate (deg/s)
Actual Rotation (Neutral Instructions)
Straight Path Instructions
Neutral Instructions
Curved Path Instructions

(a)


Dense Posts
Path error (deg)
20
15
10
5
0
-5
-10
-15
-20
-6
-4
-2
0
2
4
6
Mean eye rotation rate (deg/s)
Actual Rotation (Neutral Instructions)
Straight Path Instructions
Neutral Instructions
Curved Path Instructions

(b)

fig. 2

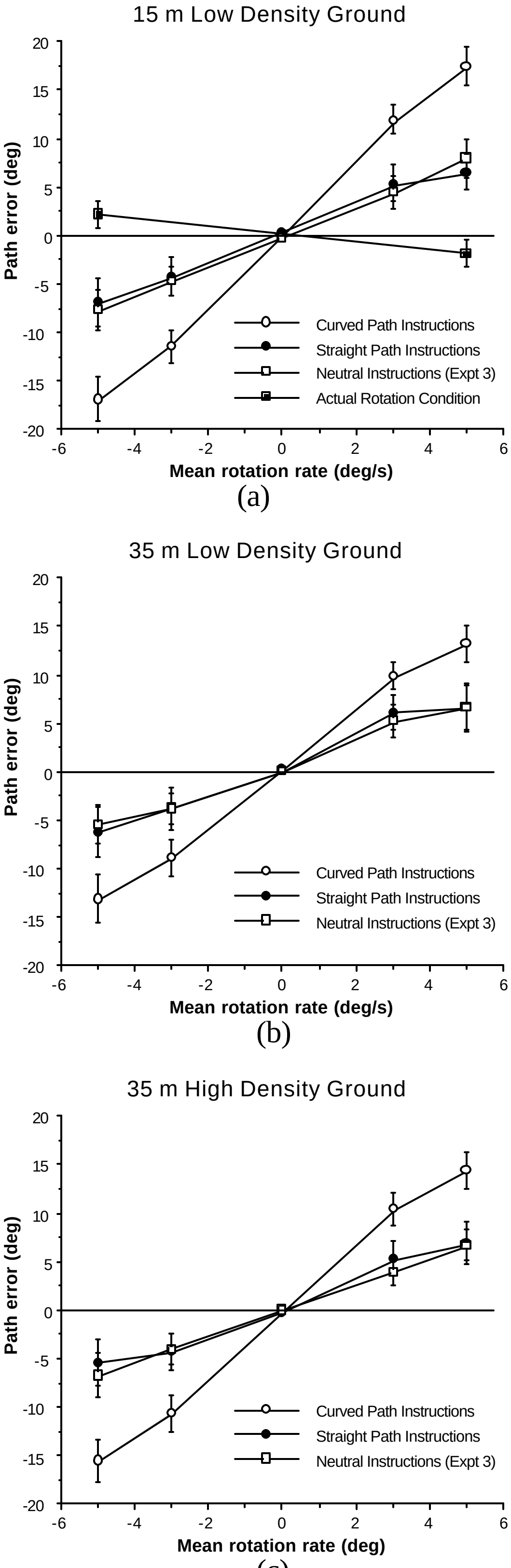


(a)

(b)

(c)

fig. 3


15 m Low Density Ground
Path error (deg)
Mean rotation rate (deg/s)
Curved Path Instructions
Straight Path Instructions
Neutral Instructions (Expt 3)
Actual Rotation Condition
35 m Low Density Ground
Path error (deg)
Mean rotation rate (deg/s)
Curved Path Instructions
Straight Path Instructions
Neutral Instructions (Expt 3)
35 m High Density Ground
Path error (deg)
Mean rotation rate (deg)
Curved Path Instructions
Straight Path Instructions
Neutral Instructions (Expt 3)
20
15
10
5
0
-5
-10
-15
-20
-6
-4
-2
0
2
4
6

(a)

(b)

(c)

fig. 4

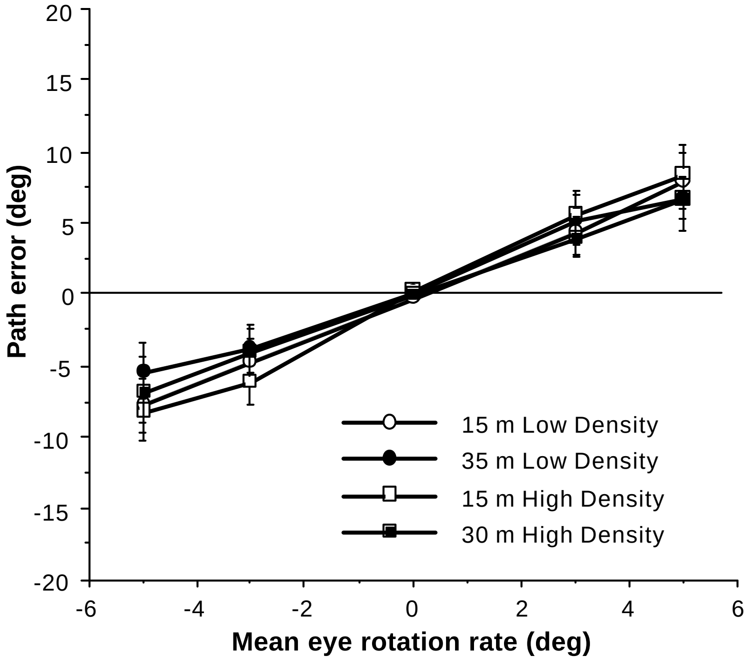

20
15
10
5
0
-5
-10
-15
-20
Path error (deg)
-6
-4
-2
0
2
4
6
Mean eye rotation rate (deg)
15 m Low Density
35 m Low Density
15 m High Density
30 m High Density

fig. 5