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Walking, looking to the side, and taking curved paths

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In two experiments, viewers judged heading from displays simulating locomotion through tree-filled environments, with gaze off to the side. They marked their heading with a mouse-controlled probe at three different depths. When simulated eye or head rotation generally exceeded 0.5 deg/sec, there was reliable curvature in perceived paths toward the fixated object. This curvature, however, was slight even with rotation rates as great as 2.6 deg/sec. Best-fit paths to circular arcs had radii of 1.8 km or greater. In a third experiment, pedestrians walked with matched gaze to the side. Measured curvature in the direction of gaze corresponded to a circular radius of about 1.3 km. Thus, at minimum, vision scientists need not worry about perceived path curvature in this situation; real path curvatures are about the same. However, at present, we can make no claim that the same mechanisms necessarily govern the two results.

Understanding how we negotiate environments has been an active and continuing research endeavor since Gibson (1950, 1958) first elucidated the issues at stake. A central interest in this area is understanding how pedestrians determine their heading (or instantaneous direction of locomotion) from optical flow (the global motion of stationary objects around a moving observer). Many different schemes have been proposed (see Cutting, 1986, and W. H. Warren, 1998a, for reviews). A side issue in the development of this research area has concerned the perception of straight versus curved paths.

Consider a situation in which one is walking along a woodland path and looking somewhat off to one side at a bird in a small tree. How we do know that this is a safe thing to do? In particular, how do we know whether we are continuing on our intended path or veering off it, perhaps toward the bird? For a brief moment, it may not matter, but discrepancies from a straight path would quickly accrue. Moreover, were we running instead of walking, those discrepancies could lead to minor injury; and if we were driving a car down a highway with gaze slightly to the side, such injury could be major indeed. Consider some literature from laboratory versions of this situation.

A Selective History of Heading Research

Methodological issues have proven both critical and limiting in research on heading perception. Early studies used analog shadow-casting systems to simulate the optical flow seen during linear translation (Kaufman, 1968; Llewellyn, 1971), and later ones used computer graphics technology (Johnston, White, & Cumming, 1973; R. Warren, 1976). Following the latter, more recent studies have divided according to whether they study motion alone (Cutting, 1986; Regan & Beverley, 1982; Rieger & Lawton, 1985; Royden, Banks, & Crowell, 1992; W. H. Warren & Hannon, 1988; W. H. Warren, Morris, & Kalish, 1988) or embrace at least some the many sources of other information found in more naturalistic environments (Cutting, Springer, Braren, & Johnson, 1992; Cutting, Vishton, Flückiger, Baumberger, & Gerndt, 1997; Li & Warren, 2000; van den Berg & Brenner, 1994; Wang & Cutting, 1999). Studies of the former variety have tended to use moving fields of dots devoid of other information about depth and layout, whereas those of the latter have used more naturalistic stimuli, with objects placed on a ground plane at different depths and other sources of information—such as occlusion, relative size, and height in the visual field—revealing that depth. Moreover, several studies have found striking differences in results for the two types of stimuli (Cutting et al., 1992; Cutting et al., 1997; Li & Warren, 2000); errors are greater and seem subject to more biases without stationary objects, ground planes, and their corollary depth information.

In addition to differences in simulated stimulus environments, there have also been differences in display techniques. One variety has simulated only translational

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motion in the optical array (Johnston et al., 1973; Kaufman, 1968; Llewellyn, 1971; van den Berg & Brenner, 1994; R. Warren, 1976; W. H. Warren & Hannon, 1988; W. H. Warren et al., 1988). In cinema, this camera motion is called a dolly. The other type of display has combined a dolly with a pan—a rotational motion, typically around a vertical axis—following a particular object just off the instantaneous heading vector (Cutting, 1986; Cutting et al., 1997; Li & Warren, 2000; Regan & Beverley, 1982; Rieger & Lawton, 1985; Wang & Cutting, 1999; W. H. Warren & Hannon, 1988; W. H. Warren et al., 1988). Displays that combine dollies and pans simulate pursuit fixations of an object off one's path, the prototypic optical behavior of pedestrians. Results with this type of display reveal the efficacy of visual information without feedback from eye or neck muscles. Several interesting findings have resulted when the use of such displays has been compared with the use of real eye movements.

First, when simulated eye or head rotation rates are less than about 1 deg/sec, the feedback from muscles controlling eye movements is unnecessary for accurate heading judgments (Royden et al., 1992; W. H. Warren & Hannon, 1988). Reanalyzing the data of Wagner, Baird, and Barbaresi (1980) on pedestrian fixation patterns, Cutting, Wang, Flückiger, and Baumberger (1999) estimated that such minimal rotations occur during two thirds of all gazes. When more rapid pursuit fixations are executed during the other third, eye muscle feedback may be necessary for accurate heading judgments (Royden et al., 1992), although not all results are consistent with such findings (Cutting et al., 1997; Li & Warren, 2000; Stone & Perrone, 1997).

Perceived Path Curvature

Second, and more pertinent to this article, simulated pursuit fixation displays can also yield an apparent path curvature (Cutting et al., 1997; Royden et al., 1992). That is, despite the simulation of a linear path off to the side of an object, one's phenomenology is often that of taking a curved path, generally toward the fixated object. Indeed, Royden (1994) showed that, optically, there is very little difference between the two situations at any given instant. She claimed that misperceptions of heading in these types of studies were due to perceived path curvature. How much path curvature is perceived or, at least, can be inferred from the data? Again, data appear to vary according to the type of display used.

The most definitive data on perceived path curvature come from the experiments of Ehrlich, Beck, Crowell, Freeman, and Banks (1998). Using the simulated pursuit fixation procedure, they assessed the amount of path curvature seen through dot clouds and over dots scattered on an invisible ground plane. For the latter, the data in their Figure 5 indicate that, for simulated eye or head rotation rates of 5 deg/sec, perceived curvature is equivalent to a circular arc with a radius of about 4 m. This is about 2.5 eye heights for an adult 1.8 m in stature. The data in their Figure 4 suggest that heading errors (and hence, curvatures) are less extreme at simulated rotation rates of 2.5 and 1 deg/sec, with mean data ranges of about 60% and 30% as great as the 5 deg/sec data, respectively. These decreases would correspond to larger circular paths with radii of about 7 and 10 m—or about 4.4 and 6.2 eye heights, respectively. In all cases, however, these are significant curvatures. They represent striking misperceptions of the stimulus situation—simulated linear translation. Moreover, although the curvature across different rotation rates was more consistent with dot-cloud stimuli, the results for dots on a ground plane were about the same.[1]

Previously, Cutting et al. (1997, Experiments 3 and 4; see also Li & Warren, 2000) had found considerable differences between results when observers judged their heading amid a dot cloud versus travelling across a cluttered plain. In particular, when viewing dot clouds, the perceived path curvature was sufficiently great that observers consistently misplaced their heading judgments to the wrong side of the actual heading, creating heading errors as great as 20°. When viewing simulated movement through a forest environment, however, observers' heading errors were about half as great, because they seldom misplaced their heading to the wrong side.

Can we compare perceived path curvatures in the two situations? Since the data from the farthest probes of Ehrlich et al. (1998, Experiment 1) were similar to those of the dot-cloud data of Royden et al. (1992) and to those of the dot-cloud data of Cutting et al. (1997, Experiment 4), we assume that the radius of curvature for the Cutting et al. (1997) data was about the same—roughly 2.5 eye heights. The radius of curvature for the corresponding forest stimuli of Cutting et al. (1997) cannot be meaningfully estimated but is surely much greater.

Therefore, using pursuit fixation displays and a technique similar to that of Ehrlich et al. (1998), we sought to measure the perceived path curvature during simulated movement through cluttered, quasi-naturalistic environments. Ehrlich et al. used stereoscopically presented probes and a dot field that stretched out in front of the observer from about 2 to 13 eye heights. Our environments, on the other hand, have typically stretched farther out to 50 eye heights or more, where binocular disparities would no longer be effective (Cutting & Vishton, 1995). Thus, instead of specifying probe depth stereoscopically, we specified it by putting the probe on the ground plane with the trees and allowing relative size, height in the visual field, and occlusion to carry the depth information.

Two Theoretical Foci, but Perhaps One

In the first two experiments, we measured the perceived path curvature in several simulated pursuit fixation situations, with more and less environmental clutter and with simulated eye or head rotation typical of pedestrian gait. The theoretical rationale for these studies was to investigate a proposition put forth by Royden (1994) that heading errors found in studies with simulated pursuit fixation displays are due to perceived path curvature. Previously, we had found substantial heading errors (Cutting et al., 1992; Cutting et al., 1997; Cutting et al., 1999) but had found only modest evidence suggesting perceived path curvature.

In a third experiment, we measured actual curvature in walked paths with gaze off to the side. This experiment had a different rationale. From the sensory-tonic field theory of Werner and Wapner (1952) and from various reports about riding motorcycles (Motorcycle Safety Foundation, 1992) and horses (Morris, 1990), we suspected that path curvature might occur here as well. In our context, the sensory-tonic field theory concerns the relations between two measures—the physically determined straight ahead, as determined by the sagittal plane of the body, and the perceived straight ahead as it deviates from it owing to, for example, head turns (Werner, Wapner, & Bruell, 1953).[2] Were there to be a mismatch between visual direction (or the perceived straight ahead; see Matin, 1986) and optical flow during linear translation, a curved path might be generated during gait (see also Warren, Kay, Zosh, Duchon, & Sahuc, 2001).

The overriding concern of this article is whether or not curvatures found in these two related situations might be the same in direction and approximately the same in magnitude. If perceived path curvature during simulated linear translation roughly matches real path curvatures during gait with intent to walk straight, two possibilities emerge. First and more speculatively, the perceived path curvature in laboratory simulations of linear translation might be linked to pedestrian behavior. At present, we would have no way to determine whether this is true, although it remains an interesting possibility. Second and more conservatively, the laboratory result considered as an artifact—whatever its cause—should not be of deep concern to visual scientists, since it matches real-world behavior.

EXPERIMENT 1

Heading, Probe Depth, and Simulated Eye or Head Rotation of 1 Deg/Sec and Less

Method

Stimuli were generated on a Silicon Graphics Indy (Model R5000) at 34 frames/sec. Viewers sat about 0.4 m from the screen, yielding 40°-wide displays seen at a resolution of about 30 pixels/deg. Each stimulus sequence was 3.5 sec in duration and consisted of simulated forward locomotion (a dolly) at 1.25 eye heights/sec (a brisk walk) with camera rotation (a pan) to keep one tree in the center of the display. The observers participated in six conditions: Three of differing clutter crossed with two of differing fixation depths, generating different ranges of simulated eye or head rotations. The differential clutter consisted of planar, otherwise featureless environments with varying numbers of schematic trees—with means of 86.8, 21.7, and 5.5 trees (with standard deviations of 6.8, 3.3, and 1.2, respectively). In every case, all the trees were distributed randomly in the environment, except for the fixation tree. The farthest tree could be as much as 62 eye heights from the observer; the nearest could be as little as 3 eye heights away. In slower rotation conditions, the initial position of the fixation tree was 31.3 eye heights from the viewer; at trial's end, it was about 26.6 eye heights away. In the marginally faster rotation conditions of this experiment, its initial and final positions were 15.6 and 10.9 eye heights away. The observers were encouraged to maintain gaze on the fixation tree. Cutting et al. (1997) and Cutting, Alliprandini, and Wang (2000) analyzed eye movement data under constrained- and free-viewing conditions, respectively. Their results compromise no analysis presented here.

All the trees were 2.3 eye heights tall, with major branching at 1.1 eye heights. Each was leafless and identical to the others in shape but was rotated to a new random orientation. The horizon was true, not truncated at a given depth plane. Relative distance was indicated by relative tree size and by the height in the visual field of the base of each tree trunk; intrinsic size was indicated by the fact that the horizon intersected each trunk so that eye height was 43% of tree height. In the displays, the sky was light blue, the ground plane was brown, and the trees were dark gray, except for the fixation tree, which was red.

At the end of each trial sequence, the last frame remained on the screen. The observers were then presented with a mobile, mouse-controlled, red vertical probe bar (2 eye heights tall). This probe could be moved in the scene at a set depth on each trial. As it was moved, it occluded farther trees and was occluded by nearer ones, thus making it appear to be *in* the environment, as is suggested in the bottom panel of Figure 1. The observers were instructed to move the probe laterally until it was in a position so that their simulated path would take them directly toward it, then to click the left mouse key. The responses were stored in a computer file. Three different probe depths were used: 14.0, 32.8, and 51.6 eye heights from the final position of the observer (and 18.8, 37.5, and 56.3 eye heights from the start position of the display sequence). We will call these the near, middle, and far probes. Sample final frames with probes at the three depths are shown in Figure 1. The logic of the methodology here, as in Ehrlich et al. (1998), is that interpolation from the observers' final position through the mean locations of the probe responses on similar trials should allow assessment of path curvature, if any. Decreasing response eccentricities with increasing probe depth would specify curvatures in the direction of simulated gaze. After the observers responded, an announcement of the upcoming trial number appeared, followed by a 1-sec pause. Should they wish, the observers could also press the central mouse key to view the trial again, although this occurred on fewer than 3% of all the trials.

Each observer watched six randomly ordered sequences of 72 trials each: 3 different probe depths × 2 sides of approach (to the left or right of the central tree) × 4 initial gaze angles (1°, 2°, 4°, and 8°) × 3 observations per trial type. Final gaze angles for the far-fixation condition were 1.2°, 2.4°, 4.7°, and 9.4°; corresponding angles for the nearer fixation condition were 1.4°, 2.8°, 5.5°, and 11.1°. Thus, the maximum simulated eye or head rotation in this experiment was 1 deg/sec. Royden et al. (1992) suggested that in simulated pursuit fixation displays, such as those used here, judgments based on rotation rates of 1 deg/sec and less did not require information from eye muscle feedback. The order of viewing the six conditions (87-, 22-, and 6-tree environments crossed with final fixation distances of 27 and 11 eye heights) was randomized across subjects in such a way that no viewer participated in the same order.

Ten Cornell University undergraduates participated singly, had normal or corrected-to-normal vision, were paid, and were naive as to the purposes of the experiment at the time of testing. The observers received a few practice trials before beginning the first sequence. No feedback was given during the course of the experiment. With practice and debriefing, the experimental session lasted about 1 h.

Results and Discussion

Basic findings. As in all our previous research, there was no effect of side of approach [$F(1,9) < 1$]. In addition, and consistent with the larger literature (e.g., Banks,

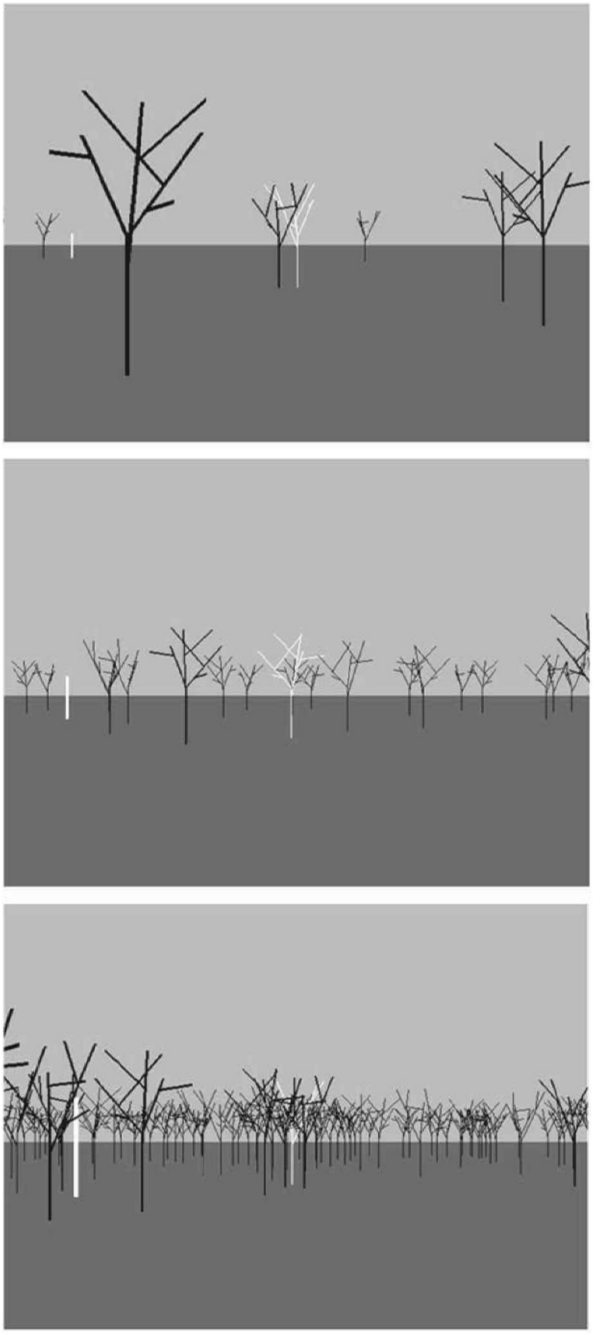

Figure 1. The central 25° × 18° portions of the screen for three final frames, one each from the three differential clutter conditions of Experiment 1. Laterally mobile probes are shown placed to the left. The top panel shows the condition with the fewest trees and the farthest probe, the middle that with intermediate trees and probe, and the bottom that with the most trees and the nearest probe. Here, central trees and probes are white; in the experiments they were red.

Ehrlich, Backus, & Crowell, 1996; Kim, Growney, & Turvey, 1996; W. H. Warren & Hannon, 1988), there was a reliable effect of gaze angle from the heading direction [$F(3,27) = 14.9$, $p < .001$]. Mean responses were 0.82°, 1.52°, 2.12°, and 3.60° for initial gaze angles of 1°, 2°, 4°, and 8°, respectively. Final gaze angles were a bit larger, as was noted above, but perhaps more important was the systematic increase in errors with increase in angle. For example, with a mean response of 3.6° and a true final gaze angle of 11.5°, the largest mean heading error was nearly 8°. This underestimation is typical of this type of research (e.g., Cutting et al., 1992; Cutting et al., 1999; van den Berg & Brenner, 1994). Royden (1994) suggested that it was caused by perceived path curvature. Others have suggested that it is a bias to respond toward the center of the screen (e.g., Cutting et al., 1992; Ehrlich et al., 1998). Elsewhere, we have argued that viewers, at least in this type of experimental situation, do not respond as if they know their absolute heading, only their general direction left or right of a particular landmark (Cutting et al., 1999) or their path between particular landmarks (Cutting et al., 2000; Wang & Cutting, 1999).

To our surprise, there was no main effect of the number of trees in the display [$F(1,9) < 1$] nor any interaction involving number of trees. Overall, response eccentricities were 2.3°, 1.9°, and 1.9°, respectively, for conditions with 89, 22, and 6 trees, respectively. We had expected absolute errors (underestimations of heading) to be a bit greater for environments with fewer trees. This trend occurred but was not statistically reliable. Previously, Cutting et al. (1992, Experiment 2) found small but reliable heading judgment differences between environments with 74 versus 5 trees. However, these differences were measured nominally (left or right of fixation) rather than absolutely (how far left or right), and perhaps more important, Cutting et al. (1992) did not use a probe technique. We assume that an observer-controlled probe provides a more accurate estimation of perceived heading. The lack of a tree density effect need not be an embarrassment to our theory (Cutting & Readinger, in press; Cutting & Wang, 2000; Wang & Cutting, 1999). The depth separations of the trees in the 6-tree environments were sufficiently large to generate many tree pairs that would be likely to crossover, converge, or decelerate apart during a trial. Thus, sufficiently salient invariants were likely present on almost all the trials.

Also somewhat surprising was the lack of a reliable effect of fixation distance [$F(1,9) < 1$], with mean responses of 1.9° and 2.2° for final simulated fixation distances of 27 and 11 eye heights. Cutting, Vishton, and Braren (1995, Experiment 1) found a significant difference for final distances of 16 and 8 eye heights. We attribute this lack to the smaller simulated eye or head rotation rates used in this experiment. In Experiment 2, we increased the range of rotation rates.

Perceived path curvature. Most important, however, there was a reliable effect of probe distance [$F(2,18) = 11.8$, $p < .001$] and an interaction of probe distance with gaze angle [$F(2,18) = 9.9$, $p < .001$]. In particular, overall response eccentricity decreased with probe distance: 2.37°, 1.93°, and 1.91° for near, middle, and far probes, respectively. Systematically decreasing response eccentricities with increasing probe distance is consistent with the idea of perceived path curvature in the direction of simulated gaze. This curvature, however, was statistically reliable only in displays at the greatest initial gaze angle (8°), where mean responses were 4.5°, 3.5°, and 2.8° [$F(2,18) = 20.3, p < .001$]. No significant probe differences were found for trials with 1° and 2° gaze angles [0.83°, 0.75°, and 0.89°, and 1.6°, 1.4°, and 1.5°, respectively; $Fs(2,18) < 1$], and although there was a reliable probe distance effect at 4° [2.5°, 2.0°, and 2.4°; $F(2,18) = 4.9, p < .02$], it could not be characterized as curvature. The data for all four gaze angles at all three probe distances are shown in Figure 2, along with the interquartile response ranges and the true paths. Data are collapsed across near and far fixations. Note that for display purposes, the ordinate of each graph is expanded by a factor of five, as compared with the abscissa.

Next, we assessed the degree of curvature in the 8° initial gaze angle data by a best-fitting circular arc to four points: the final location of the observer and the mean heading response at the three different probe depths. The amount of curvature is slight, equivalent to a circle with a radius of slightly greater than 1,400 eye heights.[3] For an observer 1.8 m in height, with his or her eyes 1.65 m above the surface, this is a circle about 2.3 km in radius. Such curvature, although statistically different than a straight path, is negligible under all practical considerations; it is equivalent to a lateral movement of about 250 μm for every step (0.75 m) taken forward. In fact, it

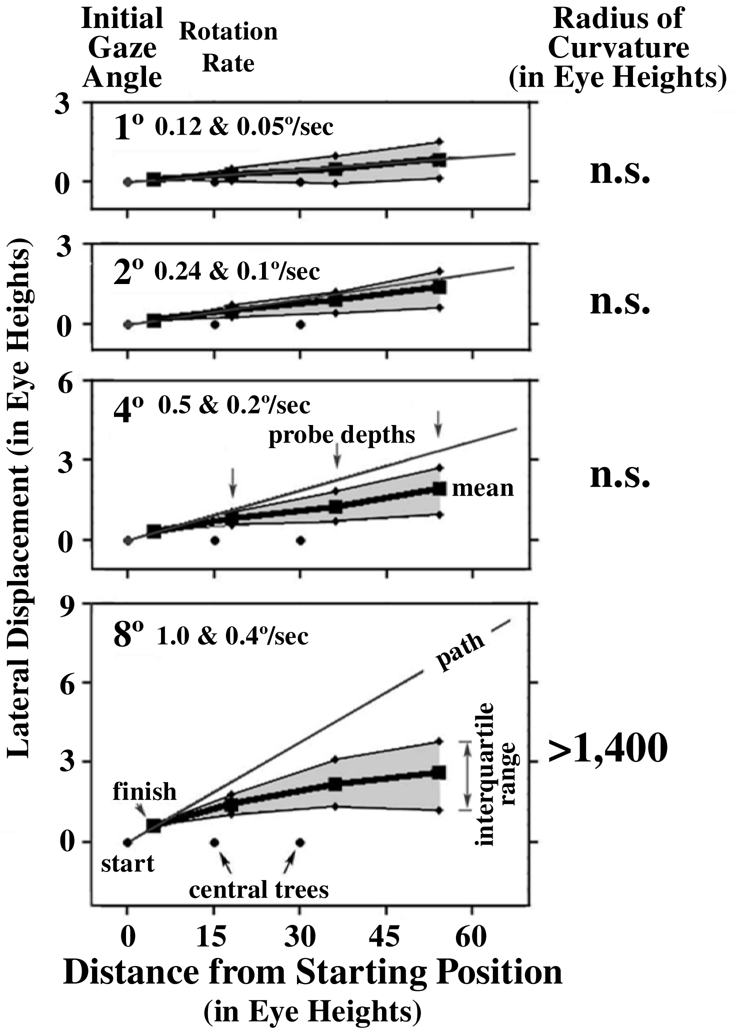

Figure 2. Probe placement results of Experiment 1, plotted as a function of initial gaze angle and probe distance. In each panel, the mean and interquartile range of responses are shown. Reliable curvature exists only in the data at an initial gaze angle of 8°, and this curvature is equivalent to a circle arc with a radius of greater than 1,400 eye heights. There were no differences across conditions of clutter, shown in Figure 1. Note that for display purposes, the ordinate is expanded five times with respect to the abscissa.

hardly seemed likely that anyone walking through any environment could, within 3.5 sec, keep a measured path straighter than one with a curvature of this degree. We tested this idea in Experiment 3.

One might have qualms about this first experiment for its relatively small rate of simulated rotation, here generally less than 1 deg/sec. Others have used simulated rotations of as much as 5 deg/sec (Royden, 1994; Royden et al., 1992). However, in a reanalysis of Wagner et al.'s (1980) pedestrian gazes during strolls through a college campus and a neighboring town, Cutting et al. (1999) found that two thirds of all such free gazes entailed pursuit fixations with rotations of 1 deg/sec or less. Thus, we are quite satisfied that the conditions and the results of Experiment 1 are in keeping with gazes executed during everyday human activity. Nonetheless, it seemed prudent to extend the range of simulated rotations.

Overview. After viewing stimuli that simulated their movement through a naturalistic environment while looking off to the side of their path, observers were probed at three distances and were asked to locate their perceived heading. Mean values of these probe positions were fit to a circular arc. With gaze-heading angles and simulated eye/head rotation rates sufficiently large (8°, and up to 1 deg/sec) some reliable perceived path curvature was obtained. This result replicates the *fact* of curvature found by Ehrlich et al. (1998). However, the radius of this curvature here was considerably greater than a mile (>2.4 km) for an adult pedestrian. This result contrasts markedly with that of Ehrlich et al., whose observers, when looking at dot-field stimuli generally without depth information, had perceived path curvatures of generally less than 10 m for the same simulated eye/head rotation rates. Also, and surprisingly, there were no differences here in perceived curvature as a function of variation in the number of trees and with different fixation distances. We felt all of these results were in need of replication, particularly with an extended range of simulated eye/head rotations.

EXPERIMENT 2
Heading, Probe Depth, and Simulated Eye or Head Rotations of Up to 2.6 Deg/Sec

Method

Ten viewers from the Cornell community were paid to participate in an experiment similar to Experiment 1. Seven were naive as to the purposes of the experiment; 3 had been in Experiment 1. There were three major differences in this experiment. First, the range of probe distances from the observer's final position was increased: Probes were placed nearer (7.8 eye heights) and farther away (57.8), as well as in between (32.8). These correspond to 12.5, 37.5, and 62.5 eye heights from the start position. Second, the fixation tree distances were decreased to 28.1 and 9.4 eye heights at the beginning of the trials (23.4 and 4.7 eye heights at the end). Third, initial gaze angles were fewer but varied through a wider range: 1°, 5°, and 9°. Decreased fixation distance and greater gaze angles increased simulated eye or head rotation rates. Final gaze angles for the farther fixation condition were 1.2°, 6.1°, and 10.8°; corresponding angles for the nearer fixation condition were 2.1°, 10.1°, and 18.1°. The last yielded a simulated eye or head rotation rate of 2.6 deg/sec. Greater rotation rates than this made the true aimpoint leave the screen, making accurate responses impossible to record with this methodology and equipment (but see Crowell & Banks, 1993). Again, each observer watched six different random sequences (three different tree densities crossed with two fixation depths), this time of 54 trials each (3 different probe depths × 2 sides of approach × 3 initial gaze angles × 3 observations per trial type). Again, no feedback was given. The session took about 50 min.

Results and Discussion

Basic findings. As in Experiment 1 and in previous research, there was no reliable effect of side of approach [$F(1,9) < 1$], but there was a reliable effect of initial gaze angle [$F(2,18) = 38.6$, $p < .0001$]. Mean response eccentricities were 1.7°, 5.9°, and 8.3°, respectively, for initial angles of 1°, 5°, and 9°. Again, there was no effect of the number of trees in the display [$F(2,18) = 1.4$, $p > .25$], with mean response eccentricities of 5.3°, 5.8°, and 4.8° for displays with 87, 22, and 6 trees, respectively. This time, however, there was a main effect of fixation distance [$F(1,9) = 15.9$, $p < .001$], with mean response eccentricities of 4.2° and 6.4° for far and near fixations, respectively. There were, however, no reliable interactions with fixation distance. There was also no difference between naive and experienced viewers.

Perceived curvature. As in Experiment 1, there was a reliable overall effect of probe distance [$F(2,18) = 14.1$, $p < .001$], with response eccentricities of 6.3°, 4.9°, and 4.7° at probe distances of 8, 33, and 56 eye heights, respectively. Again, the general decrease is consistent with some curvature in the perceived paths. Although there was no reliable decrease with probe distance for the 1° initial gaze stimuli [$F(1,9) < 1$, with means of 1.8°, 1.6°, and 1.6°], there were reliable decreases for both 5° and 9° stimuli [Fs$(1,9) > 8.9$, ps $< .001$]. For the 5° initial gaze stimuli the mean eccentricities were 6.7,° 5.8,° and 5.2°, respectively, and for the 9° stimuli, they were 10.4,° 7.3,° and 7.3°. Figure 3 shows the patterns of the mean responses and interquartile ranges at the three probe depths and for near and far fixation distances at the three initial gaze angles. As in Figure 2, the ordinate of each graph is expanded to be five times that of the abscissa. Note here the increase in interquartile range and, hence, variability in the data. This is due almost certainly to the increased range of eye/head rotation rates across the set of stimuli.

As in Experiment 1, we fit four points to a circular arc—the final observer position and the mean results at the three probe depths—to those data with a reliable probe distance × gaze angle interaction. These were the 5° and 9° initial gaze data at near and far simulated fixation depths. In all cases, the radius of those arcs was greater than 1,100 eye heights, or for a standard observer, greater than 1.8 km. This is equivalent to lateral movement of about 400 μm for every step forward. Thus, as in Experiment 1, although the curvature in the perceived

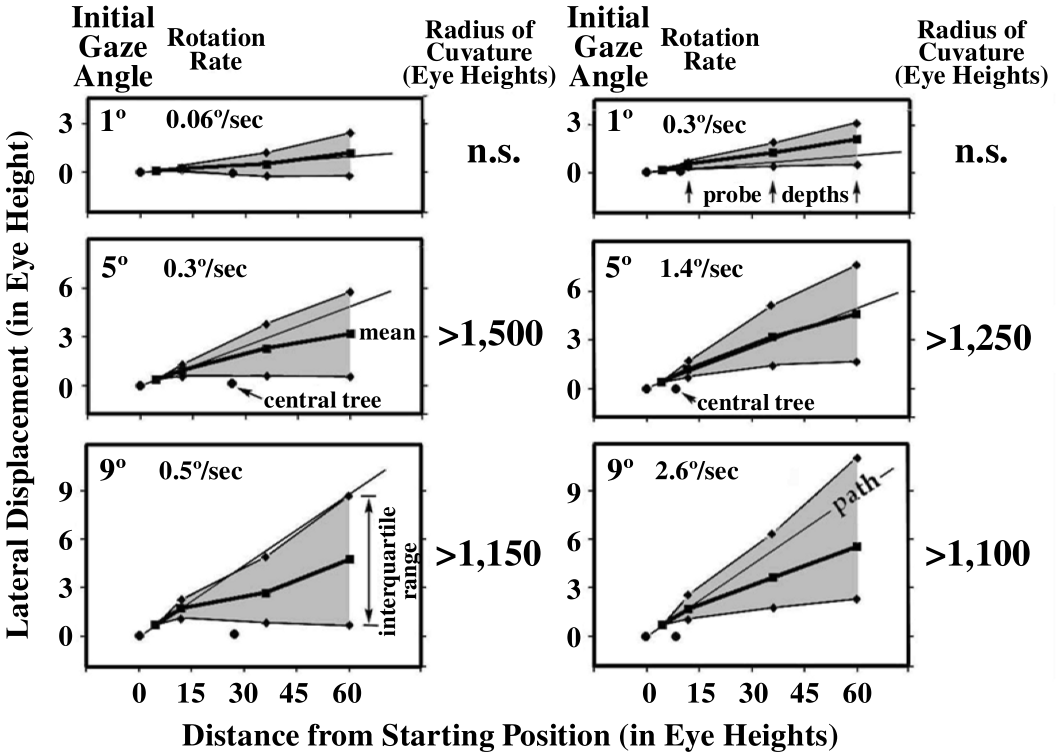

Figure 3. Probe placement results of Experiment 2, plotted by initial gaze angle and by simulated eye or head rotation rate. In no case is the perceived path curvature greater than a circular arc with a radius of 1 km. Again, there were no differences by conditions of clutter (Figure 1), and note again that the ordinate is expanded five times with respect to the abscissa.

path was again statistically reliable in some conditions, it was always negligible under practical considerations.

One might continue to argue that we have not sampled the full range of simulated rotations used in the literature, and this is true. However, not only did our display context not allow us further variation, but the Cutting et al. (1999) analysis of pedestrian gazes suggests that rotations as great as 5 deg/sec occur less than 12% of the time. Thus, we are satisfied that, in our simulations, we have sampled the eye or head rotations found during all those circumstances in which a pedestrian might wish to know his or her heading.

Overview. The results of Experiment 2 replicated and extended those of Experiment 1. Again, there was no effect of clutter, or the number of trees in the simulated environment. Exploring a somewhat greater range of initial gaze movement angles (up to 9°) and increased simulated eye/head rotation rates (up to 2.6 deg/sec), we continued to find some reliable perceived path curvature. However, again in contrast with the results of Ehrlich et al. (1998), the curvature was very small. Indeed, the radius of curvature was never tighter than a circular arc of 1.8 km.

Like Cutting et al. (1997; Cutting et al., 1999) and Li and Warren (2000), we suspect curvature differences in perceived paths in the two situations stems from the different types of stimuli used. Ehrlich et al. (1998) and many researchers before them used dot fields without information about objects and layout. In contrast, we and others have used more naturalistic environments, with objects and texture density approaching that of the real world. Cluttered environments are full of objects that anchor the observer within it. It remains possible, however, that significant path curvature would be experienced at gaze angles and rotation rates larger than those explored here. In these situations and in the real world, however, feedback from muscles generating eye movements would be available to aid the pedestrian, just as Banks et al. (1996) and Ehrlich et al. have proposed.

EXPERIMENT 3
Path Curvature Generated During Gait With Fixation to the Side

When attempting to walk in a straight line while looking off to the side, can a pedestrian avoid taking a slightly curved path? The reports of paths taken during motorcycle and horseback riding suggest that there might be some path curvature in the direction of gaze. The Motorcycle Safety Foundation (1992), for example, suggested that "riders steer in the direction they are looking.

Most riders have experienced situations in which they were unable to avoid hitting an object or defect in the roadway because their gaze was fixed on the hazard rather than on the clear path of travel" (p. XIV-4). Similarly, manuals on riding horseback encourage the rider to gaze where he or she wants the horse to go (Morris, 1990)—ostensibly, because the rider's leg muscles are potentiated to follow the rider's gaze and the horse responds to changes in the rider's posture. Both of these suggestions are in tune with Werner and Wapner's (1952) sensory-tonic field theory, which generally concerns mismatches between the perceived straight ahead and the sagittal plane of one's body. One way to generate such mismatches is with a head turn.

Were the curvatures and direction of curvatures comparable in the two situations—for a real-life pedestrian and for an observer in the laboratory looking at simulated pursuit fixation displays—we would, at minimum, have compelling evidence that the path curvature found in the experimental situations is not a worrisome artifact. It would be well within the normal variation found during human locomotion. In addition, it would be possible that there could be a theoretical connection between the two. At present, however, we would not claim that the mechanisms underlying the two are the same. Any curvature found with a pedestrian is almost certainly linked to balance and to real eye and, more likely, head movements. Any curvature found in our lab situations cannot easily be attributed to either.

Method

Ten different Cornell undergraduate students volunteered to participate individually in a task involving walking while looking. All had normal or corrected-to-normal vision, walked normally and symmetrically with ease, and were naive as to the purposes of the experiment. The session was conducted in a large lecture room with industrial carpeting. The subject was never less than 2 m from any wall. A trial consisted of the subject's taking at least seven steps (LRLRLRL) while walking on a 1.22-m-wide × 5-m-long brown sheet of wrapping paper firmly taped to the carpet. He or she wore a soft rubber boot strap over the left shoe with four snow cleats under the toes and ball of the foot. During gait, the cleats punctured the paper, producing marks for each of the four left footfalls. No subject reported any difficulty or hindrance to normal gait. At the conclusion of each trial, puncture marks were labeled for later measurement, and when necessary, the old sheet was removed and a new sheet taped to the floor.

The subjects fixated a small object placed on a wall initially 9.8 m distant. Fixation objects were glow-in-the-dark cream-colored plastic stars (8 cm in maximum extent) affixed to the wall at 1.75 m above the floor. Stars were in one of three positions: 5° to the left of their initial designated aimpoint, 5° to the right, or directly ahead and at their aimpoint. For the first two conditions, mean final gaze gait angle was 10.5°. Since mean walking duration was about 4.2 sec, mean eye or head rotation rate was about 1.5 deg/sec, comparable to the upper range of rotation rates in Experiment 2. No subject reported a problem seeing the star during any trial. Since gaze was fixed at eye height, the end of the brown wrapping paper used to measure footfalls was at least 20° away from the fovea. Even in room-lit conditions, resolution at this eccentricity is not sufficient to register locations of puncture marks or our notational marks from previous trials. Puncture marks also could not be felt in any way. Thus, there was no guidance information from previous trials to aid ongoing trials.

The experimental session consisted of 18 trials per subject: 3 looking conditions (left, right, and straight ahead) × 2 lighting conditions (room lit and room darkened) × 3 repeated measures. The three repetitions were always completed as a block, with the six blocks ordered randomly for each subject. At the beginning of each trial, the subject located him- or herself at a designated starting point marked on the rolled-out paper. Instructions were to fixate the star and walk straight ahead, down the sheet of paper as normally as possible (with the reminder that "straight ahead" would not always be the gaze direction). At the conclusion of each walk, the subject stepped off the sheet and returned to the starting position.

For room-darkened conditions, instructions were given, and observers were allowed to orient themselves, before the lights were extinguished. After walking was completed, the lights were turned back on to eliminate dark adaptation. To ensure the unavailability of light, we ran all the subjects at night, with windows blackened by light-inhibiting shades. No subject reported being able to see anything other than the glowing fixation star during the darkened conditions. We expected the subjects to be relatively unhindered in the dark. For example, the subjects of Loomis, Da Silva, Fujita, and Fukusima (1992) and Philbeck and Loomis (1997) walked easily and confidently in the dark, without gross deviations from their intended path, for periods longer than those studied here.

No feedback was given during the experimental session, which lasted approximately 20–30 min, including debriefing. Two-dimensional coordinates (lateral position from the left edge of the paper roll and forward position along it) were entered in a computer data file for each left footfall on each trial. Angular deviations from straight ahead—to the left (<0°) and to the right (>0°)—were recorded for each of the two triplets of successive left footfalls and then summed.

Results and Discussion

Somewhat surprisingly, there was no difference between the room-lit and the room-darkened conditions [$F(1,9) < 1$]. This is almost surely due to the fact that the duration and distance of seven steps was relatively short; we believe that longer distances with more footfalls would likely show a difference. We then collapsed across lighting conditions to consider differences among the three gaze conditions. Summed angular deviations of left footfalls revealed that the observers veered a total of −0.13° to the left when looking to the left; while looking straight ahead, they veered 0.12° to the right; while looking to the right, they veered 0.35° to the right. Thus, there was a slight tendency for path curvature to be in the direction of gaze. Differences across conditions were reliable [$F(2,18) = 4.0, p < .04$]. The difference in absolute curvatures to the left and to the right seems likely to be due to the fact that the left foot was on the inside in the gaze-left conditions and on the outside for the gaze-right condition, generating a larger arc for the latter. The mean absolute difference in deviations left and right from looking straight also revealed a reliable difference [$F(1,9) = 9.4, p < .02$]. The resulting mean total curvature in the looking-to-the-side conditions was 0.23°, which is equivalent to walking along a curved path with a radius of about 800 eye heights (or 1.3 km). Thus, we

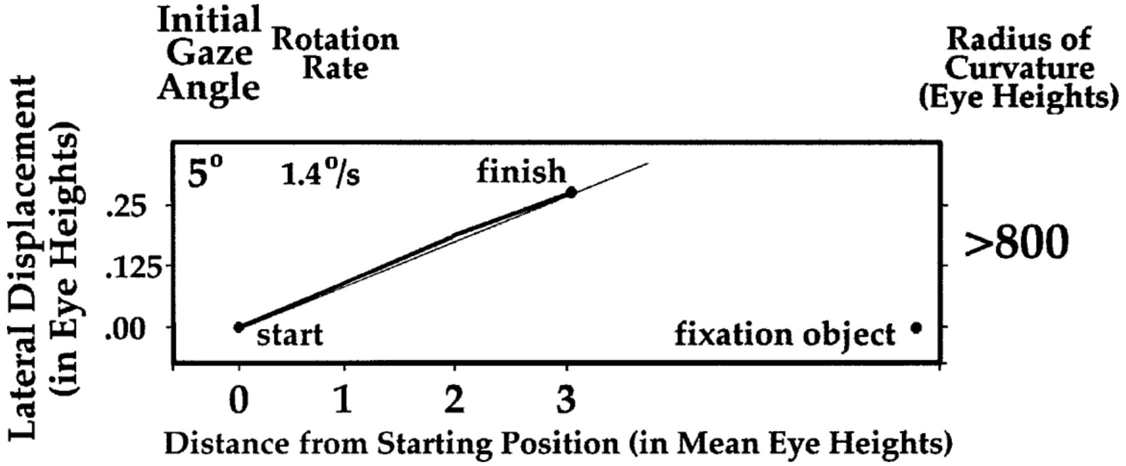

Figure 4. Mean footfall location results of Experiment 3, plotted in the same general manner as the simulation pursuit fixation results of Experiments 1 and 2. Here, initial and final footfall positions were fixed to fit the straight path, and the two intermediate footfalls allowed to deviate from that path. The ordinate is expanded 4.5 times with respect to the abscissa.

replicated in real life the general degree of curvature in the perceived paths in the laboratory. Results are plotted in Figure 4, displayed as if all gazes were to the right. To plot these data, the mean locations of the initial and final footfalls were fixed in position, with the two intermediate footfalls allowed to deviate. Again, note that the ordinate is expanded, as compared with the abscissa.

Compare the path curvatures seen in Figures 2 and 3 for the simulated pursuit fixation stimuli with those of Figure 4 for the actual paths taken by pedestrians. The curvatures are about the same. The difference between radii of about 800 and 1,100 eye heights is well within measurement error. One small difference did occur. The reliable curvatures seen for the simulated translation data are always closer to the fixation object than is the true path. The mean pedestrian path taken in Experiment 3 lies somewhat outside the intended path as plotted. That is, the pedestrians' early footfalls step slightly away from the fixation object, then curve back toward it. Such a result is consistent with the views of Rushton, Harris, Lloyd, and Wann (1998), Harris and Rogers (1999), and W. H. Warren et al. (2001), whose accounts suggest an adjustment of body-centered and head-centered coordinates.

Finally, in room-lit conditions, we noticed that the observers chose to turn their heads to maintain fixation on the off-path target. This renders the sensory-tonic field theory potentially more relevant, since Werner et al. (1953) found the perceived straight ahead to be displaced in the direction of a head turn. To be sure, our subjects may have executed eye movements as well, but we suspect that path curvature is predicated on postural adjustments and that these are more a function of head turns than of eye rotation.

Overview. Pedestrians often take slightly curved paths when they walk. In particular, this curvature appears to be generally in the direction of one's gaze. The neural mechanisms that generate this type of curvature are not completely clear, although they would seem to be the same as those involved in the curvatures of motorcycle and horseback riding. The idea is an elaboration of the notion that gaze controls posture and balance (Gibson, 1958; W. H. Warren, 1998b). A gaze with one's head to the side can generate a turn on a motorcycle, and a horse can read posture and balance. Since posture and balance are not involved in the laboratory settings of Experiments 1 and 2, we can make no firm claim that the perceived path curvature found there is due directly to the same mechanisms.

GENERAL DISCUSSION

Looking Where You Go and Going Where You Look

Much work on human navigation has assumed that we generally locomote first, then look, or try to look, where we are going. Indeed, the work presented here assumes that the visual goal of locomotion is to determine one's absolute heading vector with some accuracy. Gibson's (1950, 1958, 1966) search for adequate information about one's heading is predicated on the idea that the important information, for him the focus of expansion, lies along the heading vector. However, pedestrians spend very little time looking near their heading vector. Wagner et al. (1980) found that pedestrians look within 5° of their heading less than 10% of the time, although Calvert (1954) found that as car drivers increased their velocity, they spent more of their time looking at or near their heading vector. Recently, our results (Cutting et al., 2000; Cutting et al., 1999; Wang & Cutting, 1999) suggested that adequate information about heading for pedestrians is found just off their heading vector and that this is where they look and why (Cutting et al., 2000).

Although it is quite clear that pedestrians spend some time looking where they are going, one needs to consider the task and goal. Most often, a pedestrian chooses a goal, looks at it, and then walks toward it, periodically checking on interim progress. Thus, the task of walking—and indeed, driving, skiing, and flying—is one of visually picking a local destination and then attaining it. Thus, beyond simply looking where one is going (which a pedestrian occasionally needs to do), one needs to go where one looks: choose a goal first and then head in its direction. It is clear we do this and that we do it with considerable accuracy (Harris & Rogers, 1999; Rushton et al., 1998; Wann & Land, 2000; Wann, Rushton, & Lee, 1995). This idea is a bit more sophisticated than former racecar driver Bob Bondurant's suggestion to high-performance driving students: "Look where you want to go" (Bondurant & Blakemore, 1998, p. 107). Bondurant's admonition simply seems to promote the efficacy of foveal vision.

Beyond needs for acuity, there is a tendency, whether cognitively desired or not, to go toward a fixated object. The admonition of the Motorcycle Safety Foundation (1992), for example, is not to look at hazards because you are likely to run into them; instead, one should look along a safe path through the hazards. Moreover, the suggestion of horseback riding manuals to look where you want the horse to go is even more insightful. In conjunction with other aids (e.g., movements of the reins, etc.), Morris (1990) discussed rider strategy and suggested the following:

> When [the rider] turns his head in the new direction he anticipates turning, his body and weight shift, giving a subtle signal to the horse slightly in advance of the more direct aids to turn; the horse then becomes more responsive to the actual aids when given. (p. 27)

Experiment 3 shows that these adjustments can affect gait as well. Recently, Readinger, Chatziastros, Cunningham, Cutting, and Bülthoff (2001) found similar curvature for car drivers in a driving simulator.[4] However, W. H. Warren et al. (2001) have shown that both egocentric goal direction and optical flow play important roles in navigation and that optical flow increasingly dominates as its information becomes richer.

Most important for the purposes of this article, there is a similarity between the results of Experiments 1 and 2 for simulated travel through simulated environments and the results of Experiment 3 for natural gait in a real room. In the first case, when one looks off a bit to the side, one's heading judgments at different distances conform to a modestly curved path. In the second case, when one looks off to the side, one actually walks in a modestly curved path. Moreover, the extent of curvature in both cases is about the same, with a circular radius of about a kilometer or more. Thus, at minimum, the extent of perceived curvature under conditions of simulated travel through a simulated environments should not be a worry for vision scientists—at least, when those environments are reasonably cluttered. If such curvature is simply an artifact, it is no greater than the actual curvature taken by pedestrians in real environments. We can make no claim that the same mechanisms are involved in the regulation of gait as measured in the real world and the detection of one's heading as measured in the laboratory from pursuit fixation displays, but the idea remains tantalizing.

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NOTES

1. Most of the experiments of Ehrlich et al. (1998) involved a moving fixation object and a stationary field of dots; those of our previous work (Cutting et al., 1992; Cutting et al., 1997; Cutting et al., 1999) and the present experiments used a fixation object attached to the ground plane. It might be thought that this could account for some of the differences reported here. However, in an attempt to replicate van den Berg and Brenner (1994), Ehrlich et al. (1998, Experiment 4) performed one experiment with a stationary fixation object and reported very similar conclusions. Indeed, a comparison of their Figure 12 with their Figure 4 shows virtually no difference, which means that the curvatures reported in their Figure 5 would generally apply to the stationary-object fixation conditions as well.

2. Obviously, Werner and Wapner's (1952) sensory-tonic field theory is not at the forefront of contemporary cognitive science. However, it was an early forerunner to more modern concerns about perception (hence the term *sensory*) and action (or muscular dispositions; hence the term *tonic*) as they go together (using the Gestalt/mathematical idea of a *field*). This theory was also part of a wider, antibehaviorist concern at midcentury with the organism's contribution to perception. The theory was not as widely tested as contemporary notions of the interdependency of perception and action. Its proponents focused primarily on perception during postural adjustments of human subjects. These were typically body tilts (following the then widespread interest in field dependence and independence) and twists away from symmetry along the sagittal plane. Results were often discussed with respect to compromises between, or adjustments of, coordinate systems—head, body, and environment—although these were not formalized.

3. We note that the path curvatures measured for Ehrlich et al. (1998) and those here were measured differently. For the former, we took them directly from coordinates in their Figure 5, then worked backward to the data in Figure 4, which show increasing path error as a function of increasing rotation rate, to compare them with the data of Cutting et al. (1997). In Experiments 1 and 2 here, we computed them from probe distances and angular deviations from the fixation object. Note, however, that once curvatures are assessed, it no longer matters how they were computed; this process is similar to coordinate transformation, leaving results in the same coordinates (here, curvature radii).

4. Readinger et al. (2001) found that drivers, when looking off to the side, had a slight tendency to steer in the direction of their gaze when driving over a relatively unmarked surface. However, among other results, they found the same effect when the steering wheel controls were reversed (as the top of the wheel moves left, the car curves right). This effect, violating normal stimulus–response compatibility, seems quite the opposite of a prediction from the sensory-tonic field theory.

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