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Jonathan W. Kelly, *Vanderbilt University*
Timothy P. McNamara, *Vanderbilt University*
Bobby Bodenheimer, *Vanderbilt University*
Thomas H. Carr, *Michigan State University*
John J. Rieser, *Vanderbilt University*

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The shape of human navigation: How environmental geometry is used in maintenance of spatial orientation

Jonathan W. Kelly[1], **Timothy P. McNamara**[1], **Bobby Bodenheimer**[1], **Thomas H. Carr**[2], and **John J. Rieser**[1]

1 *Vanderbilt University*

2 *Michigan State University*

Abstract

The role of environmental geometry in maintaining spatial orientation was measured in immersive virtual reality using a spatial updating task (requiring maintenance of orientation during locomotion) within rooms varying in rotational symmetry (the number of room orientations providing the same perspective). Spatial updating was equally good in trapezoidal, rectangular and square rooms (1-fold, two-fold and four-fold rotationally symmetric, respectively) but worse in a circular room (∞-fold rotationally symmetric). This contrasts with reorientation performance, which was incrementally impaired by increasing rotational symmetry. Spatial updating performance in a shape-changing room (containing visible corners and flat surfaces, but changing its shape over time) was no better than performance in a circular room, indicating that superior spatial updating performance in angular environments was due to remembered room shape, rather than improved self-motion perception in the presence of visible corners and flat surfaces.

When moving through the environment, we use myriad cues to remain oriented to our surrounds and reorient when we get lost. A wealth of research on spatial orientation has focused on two categories of cues to spatial orientation: geometric and featural cues (for review, see Cheng & Newcombe, 2005). Geometric cues are provided by extended environmental surfaces, like the shapes formed by room walls or intersecting streets. Here we focus on geometric cues provided by room shape. Featural cues consist of non-geometric properties, such as colors and textures, which cannot be described solely in geometric terms. Natural scenes typically contain both geometric and featural cues. Experiments testing the relative contributions of these cues to human navigation commonly use a disorientation paradigm, initially developed to investigate spatial orientation in rats (Cheng, 1986). In the typical paradigm, participants learn to identify a single corner within a rectangular enclosure. Participants are subsequently blindfolded and turned until they lose track of their orientation within the environment. After disorientation, participants attempt to relocate the learned corner. A common finding is that human use of geometric cues during reorientation is nearly ubiquitous, whereas the use of featural cues depends on participant age, environment size, and secondary tasks (Cheng & Newcombe, 2005).

Address correspondence: Jonathan W. Kelly, Department of Psychology, Vanderbilt University, 111 21st Ave South, Nashville, TN 37203, Email: jonathan.kelly@vanderbilt.edu.

Although environmental geometry can provide an unambiguous cue to self-location, most research on reorientation has employed geometrically ambiguous environments. For example, rectangular rooms contain diagonally opposite corners sharing the same geometric properties (the same angle and ratio of connecting wall lengths). Disoriented adults attempting to reorient within a rectangular room split their responses evenly between the two geometrically equivalent corners (Hermer & Spelke, 1994, 1996), indicating their sensitivity to environmental geometry. According to Gallistel (1980, 1990), disoriented participants reorient by matching geometric properties of the perceived and remembered environments. Due to ambiguities in the best match, reorientation performance in rectangular and square rooms falls to approximately 50% and 25%, respectively. This performance difference between rectangular and square rooms is predicted by the fact that rectangular rooms contain two geometrically equivalent room orientations, whereas square rooms contain four. In other words, the environments differ in their rotational symmetry, or the number of possible room orientations which provide the exact same perspective. In a preliminary investigation using the room shapes depicted in Figure 1, reorientation performance was approximately inversely proportional to room rotational symmetry[1].

Although the role of geometric cues in reorientation is well documented, their role in *maintenance* of orientation remains an open question. Navigation performance often hinges on the ability to maintain an accurate sense of orientation during self-movement. In fact, successful maintenance of orientation often obviates the need for reorientation. Although rotational symmetry clearly influences reorientation performance, it is unknown how it affects maintenance of spatial orientation during locomotion. In environments of ∞-fold rotational symmetry (Figure 1, circular room), self-position and orientation can only be known through path integration, whereby internal (vestibular and proprioceptive) and external (optic and acoustic flow) motion cues are integrated over time (see Loomis, Klatzky, Golledge & Philbeck, 1999). Indeed, Chance (2000) found that errors in pointing to the path origin increased with increasing path segments when walking within a circular virtual room. In environments with 1-fold rotational symmetry (Figure 1, trapezoidal room), self-position and orientation can be directly obtained by matching geometric properties of the remembered and perceived environments, and path integration may not be needed. In environments of intermediate rotational symmetry, self-position might be determined through a combination of geometric cues and path integration.

The current experiments address the role of geometric rotational symmetry in maintenance of orientation. We expected performance in maintaining orientation to degrade as geometric cues became more ambiguous indicators of self-position and orientation. Because maintenance of orientation may be augmented by path integration, the effect of rotational symmetry might be less pronounced in our maintenance of orientation task than in a typical reorientation task.

These experiments employed immersive virtual reality (VR), where participants' translations and rotations through the physical world resulted in concomitant changes in the virtual scene. The use of VR is supported by recent findings that spatial memories are organized (Kelly & McNamara, 2008) and updated (Kelly, Avraamides & Loomis, 2007; Williams et al., 2007) similarly in real and virtual environments.

Experiment 1

Participants attempted to keep track of a learned location while walking through the environment. This spatial updating task (adapted from Chance, 2000) was performed within

[1]Average reorientation performance of eight participants in trapezoidal, rectangular, square and circular virtual environments was 88.8%, 42.5%, 20.0%, and 3.8%, respectively. Chance was 8.3%. Environment details are provided below in the description of Experiment 1.

rooms of 1-fold (trapezoidal), 2-fold (rectangular), 4-fold (square), and ∞-fold (circular) rotational symmetry. If rotational symmetry affects maintenance of orientation in the same way that it affects reorientation, then spatial updating performance should be inversely related to rotational symmetry, with best performance in the trapezoidal room and worst performance in the circular room. This trend should be most evident after extensive walking and turning, which results in impoverished estimates of self-position through path integration (Rieser & Rider, 1991), perhaps causing greater reliance on visual information.

Method

Participants—Eight men and eight women from the Nashville community were paid for participating. Average age was 22.3 years (range 18–29).

Stimuli and Design—Virtual environments were viewed on an nVisor SX head mounted display (HMD; NVIS, Reston, VA), which presented stereoscopic images at 1280×1024 resolution, refreshed at 60 Hz. HMD field-of-view was 60° diagonal. Graphics were rendered using Vizard software (WorldViz, Santa Barbara, CA) on a 3.0-GHz Pentium 4 processor with a GeForce 6800-GS graphics card. A three-axis orientation sensor (InertiaCube2; Intersense, Bedford, MA) tracked head orientation, and an optical tracking system (PPTX4; WorldViz, Santa Barbara, CA) tracked head position. Graphics displayed in the HMD were updated based on sensed head position and orientation. As such, participants' physical movements resulted in smooth visual movements through the virtual world.

The environment contained 12 posts, equally spaced around a 3 m diameter circle (Figure 2). Each post was 2 m tall and 10 cm in diameter. Post color and visibility were controlled by the experimenter. The surrounding room was circular, square, rectangular, or trapezoidal (Figure 1). Room walls were textured with a repeating brick pattern, and the floor and ceiling were textured with a carpet pattern. All rooms were 2 m tall, with a wall surface perimeter of 21 m. The circular room was 6.68 m in diameter, the square room was 5.25×5.25 m, the rectangular room was 7×3.5 m, and the trapezoidal room was 8×5.5×5.5×2 m with two 40° corners and two 140° corners.

On each trial, participants attempted to remember the location of a target post while walking to a sequence of other posts. Independent variables were the rotational symmetry of the surrounding room (1-fold, 2-fold, 4-fold or ∞-fold) and the length of the walked path (two, four, or six segments). Both variables were manipulated within participants. Rotational symmetry was blocked and counterbalanced. Each block (corresponding to one of the four room shapes) contained six trials, consisting of two repetitions of each trial type. Path length was randomized within each block.

At the end of the walked path, participants attempted to point to the location of the target post from among the 12 possible post locations. Absolute pointing error was the primary dependent measure, calculated as the absolute angular difference between the correct post and the selected post. Although participants pointed while standing at the terminal post, pointing error was measured from the center of the post configuration, consistent with previous work (Chance, 2000).

Procedure—After providing informed consent, participants received instructions and performed two practice trials. Practice trials followed the same procedures as experimental trials, but the virtual room was replaced with a large grassy ground plane.

Upon first viewing each environment, participants saw 12 gray posts arranged in a circle around them. Upon initiation of each trial, all posts except for one were removed from view, and the remaining target post was colored red. Participants were told to remember the red post's location for the ensuing trial. Participants walked to the red post, which disappeared upon their arrival, and a green post appeared in another location (randomly selected from the remaining 11 post locations). In this manner, participants walked to a sequence of green posts, leading them along a path through the environment. Upon reaching the final post, the room walls disappeared and the circle of twelve gray posts reappeared. Room walls were removed so that participants had to maintain a sense of spatial orientation during movement, rather than attempting to reorient during the response stage. Participants indicated the location of the target post by selecting one of the twelve gray posts. After responding, the room walls reappeared along with the red post in a new location, and the next trial began. Feedback was never provided.

Results

Absolute pointing error (Figure 3) was analyzed in a 2×3×4 mixed-model ANOVA with terms for gender, path length, and rotational symmetry. Significant main effects of path length [$F(2,28)=5.24$, $p=0.012$, $\eta_p^2=.27$] and rotational symmetry [$F(3,42)=3.16$, $p=0.034$, $\eta_p^2=.18$] were qualified by a significant interaction between path length and rotational symmetry [$F(6,84)=2.27$, $p=0.045$, $\eta_p^2=.14$]. Contrasts were conducted to further evaluate this interaction. When path length increased from 2 to 6 segments, errors in the circular room increased relative to errors in the other three environments [$F(1,14)=8.96$, $p=0.01$, $\eta_p^2=.39$]. Additionally, men ($M=27.2°$, $SE=3.32°$) were significantly more accurate than women [$M=45.0°$, $SE=6.16°$; $F(1,14)=6.48$, $p=0.023$, $\eta_p^2=.32$].

Discussion

Participants in the circular room became increasingly disoriented with increasing path segments, resulting in larger errors after walking longer paths. This was expected because path integration is subject to noise, which accrues while walking and turning. However, errors did not increase with increasing path segments when walking within the square, rectangular, or trapezoidal environments, where performance was comparable in all three angular rooms. This is a significant departure from the results of our preliminary disorientation experiment (see Footnote 1), where reorientation performance was inversely related to room rotational symmetry.

There are at least two possible reasons why spatial updating performance was equally good in all angular environments. First, participants in Experiment 1 may have used the shape of the angular environments to remain oriented throughout the task, and therefore never needed to reorient completely. Gallistel (1980, 1990) proposed that disoriented participants can recover self-position and orientation by aligning geometric properties (e.g., a symmetry axis) in the remembered and perceived environments. After disorientation, this alignment process is error-prone in environments with greater than one-fold rotational symmetry because of the ambiguous relationship between remembered and perceived room orientations. But in the spatial updating task in Experiment 1, participants may have continually performed this alignment process during locomotion, avoiding the ambiguity altogether. By mentally labeling one direction in the remembered and perceived environments as “north” (e.g., selecting one direction along a symmetry axis), participants may have been able to track their orientation within the environment, regardless of rotational symmetry. The circular room was not amenable to this strategy, because the environment was insufficient to identify the necessary geometric properties.

A second possibility is that the corners and flat surfaces in the angular environments improved the accuracy of path integration by improving self-motion perception. Whereas body-based self-motion cues were available in all environments, visual self-motion cues might have been enhanced in the angular environments. At the extreme, optic flow from the wall texture was the only visual cue accompanying self-rotation in the center of the circular room, whereas rotation in the center of the angular environments was signaled by optic flow as well as changing perspective information as corners and surfaces moved in and out of view. Experiment 2 addressed whether improved spatial updating performance in the angular environments was due to 1) remembered room shape or 2) more accurate path integration in the presence of visible corners and surfaces.

Experiment 2

Participants performed spatial updating within three virtual rooms: a circular room, a square room, and a *shape-change* room, in which the shape of the room changed during self-movement. In the shape-change room, the orientation of each wall changed when participants faced directly away from it. In this way, flat surfaces and corners were visible during locomotion, but room shape could not be used as a stable frame of reference.

Method

Participants—Nine men and nine women from the Nashville community were paid for their participation. Average age was 23.8 years (range 18–32).

Stimuli, Design and Procedure—Stimuli, design and procedures were similar to Experiment 1. The virtual room was circular, square, or shape-changing. Circular and square rooms were identical to those in Experiment 1. The shape-change room comprised four walls that rotated independently. Each wall rotated when participants faced orthogonally away from it, and rotation angle was randomly sampled from a range between ±40° relative to the wall angles in the square room, with a minimum rotation of 10° from the previous angle. Rotated walls were adjusted in length to ensure that wall rotation did not result in gaps between walls. In this way, wall surface orientations were stable within participants' fields-of-view, and changed when participants faced away from the wall.

Results

Absolute pointing error (Figure 4) was analyzed in a 2 (gender) × 3 (path length) × 3 (room) mixed-model ANOVA. Significant main effects of path length [$F(2,32)=21.71$, $p<0.001$, $\eta_p^2=.58$] and room [$F(2,32)=6.67$, $p=0.004$, $\eta_p^2=.29$] were qualified by a significant interaction between path length and room [$F(4,64)=6.46$, $p<0.001$, $\eta_p^2=.29$]. Contrasts showed that this interaction was due to the increased error in the circular and shape-change rooms compared with the square room when path length increased from 2 to 6 segments [$F(1,16)=23.25$, $p<0.001$, $\eta_p^2=.59$].

Discussion

Replicating Experiment 1, performance in the circular room degraded with increasing path segments, whereas performance in the square room was unaffected by path segments. Similar to performance in the circular room, performance in the shape-change room also degraded with increasing path segments, indicating that the improved performance in the square room was due to the consistent shape of the room, rather than more accurate path integration in the presence of corners and flat surfaces.

General Discussion

These experiments explored the role of environmental geometry in maintaining spatial orientation during locomotion. In Experiment 1, spatial updating performance in a circular environment degraded with increasing path length, but was unaffected by path length in three angular environments varying in rotational symmetry. Performance in the shape-change room in Experiment 2 indicates that the improved performance in angular environments was due to remembered room shape, rather than improved path integration in the presence of visible corners and flat surfaces. The effect of rotational symmetry on spatial updating performance is distinct from its effect on reorientation performance, which systematically decreased with increasing rotational symmetry (Footnote 1). The latter finding indicates that spatial orientation functions similarly in real and virtual environments, as the effect of rotational symmetry on reorientation parallels similar findings in real environments, despite subtle changes in task and stimuli (e.g., object locations in previous reorientation experiments were coincident with room corners).

To explain these findings, we draw upon the theoretical framework proposed by Mou, McNamara, Valiquette, and Rump (2004) and Gallistel's (1980, 1990) concept of matching geometric properties between remembered and perceived environments. According to Mou et al., egocentric and environmental cues are used to select a reference axis upon first experiencing an environment. This reference axis might correspond to a symmetry axis (Cheng & Gallistel, 2005; Mou, Zhao, & McNamara, 2007), and could serve as the geometric property used to match remembered and perceived environments, allowing heading to be tracked relative to the reference axis (it is possible, however, that other geometric cues are also used to compare perceived and remembered environments). According to our interpretation, maintenance of orientation in Experiment 1 required that the accuracy of participants' heading estimates exceeded the accuracy necessary to define the reference axis. For example, the orientation of a symmetry axis in the square room must be represented within +/−45° of its actual orientation to avoid confusion with geometrically equivalent symmetry axes. If perceived heading degraded beyond +/−45°, participants would have confused the selected reference axis with another symmetry axis, resulting in large errors. Because performance in the square room was quite good, we infer that participants in Experiment 1 estimated their headings within +/−45° of their actual headings, and this was sufficient for maintenance of orientation within trapezoidal, rectangular and square rooms. Performance in the circular room was worse because the geometrically uniform environment required participants to perfectly represent the selected reference axis, and cumulative errors in path integration resulted in errors in tracking the reference axis. Performance in the shape-change room might have been worse because the environmental axes continually changed, and so matching the symmetry axes of remembered and perceived environments would produce large errors. After explicit disorientation (Footnote 1), participants could only guess at the correct match between remembered and perceived environments, and reorientation performance was therefore monotonically related to room rotational symmetry.

One limitation of the path-integration task used here is that participants responded by selecting from a circular array of possible target locations. Thus the task only required participants to indicate an orientation, not a position, and a free-response task could be used to overcome this limitation. Furthermore, future work should benefit from a Bayesian approach to understanding the relative contributions of path integration and environmental cues (e.g., room shape) during navigation (Cheng, Shettleworth, Huttenlocher & Rieser, 2007; Nardini, Jones, Bedford & Braddick, 2008).

These findings advance our understanding of how environmental geometry influences spatial orientation. According to our theory, path integration is used to maintain a sense of conceptual "north" (possibly along an environmental symmetry axis) during self-motion, allowing for accurate matching between perceived and remembered environmental properties. The resulting effect of rotational symmetry on maintenance of orientation is distinct from that on reorientation.

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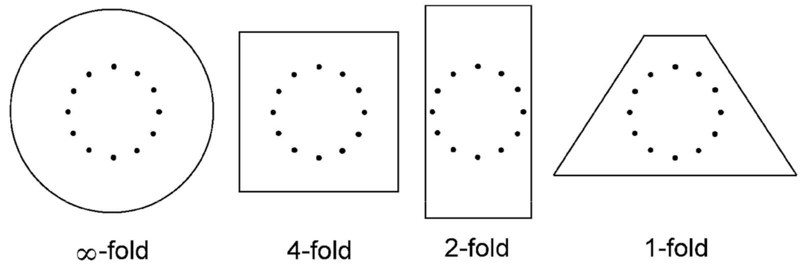

Figure 1.
Environments and stimuli used in Experiment 1. Rotational symmetry of the surrounding room decreases from left to right. Filled circles represent locations of posts used in the path integration task.

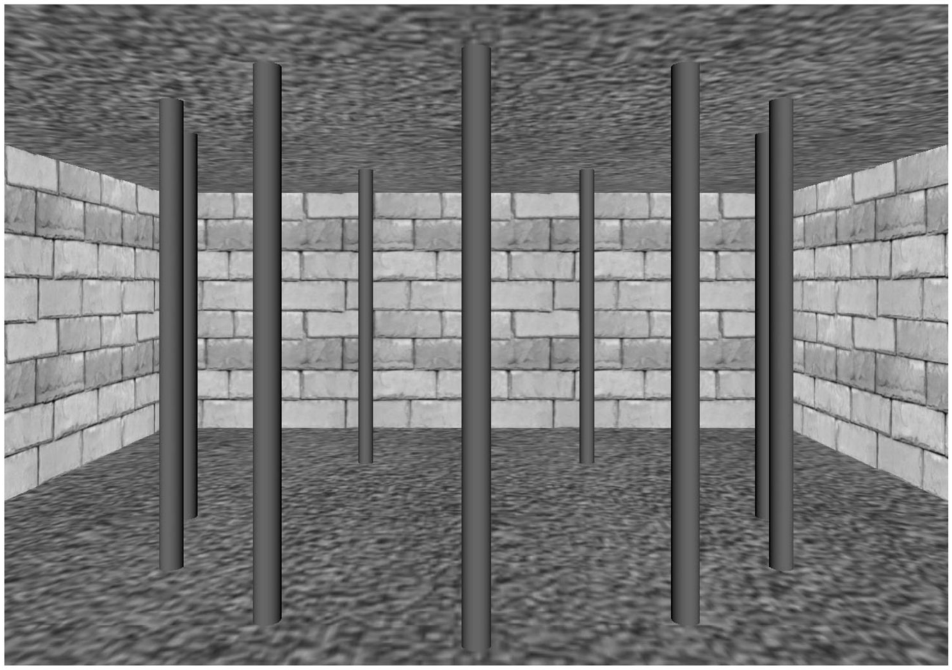

Figure 2.
Perspective view of the square room, from outside the circle of posts (participants never actually experienced this outside view).

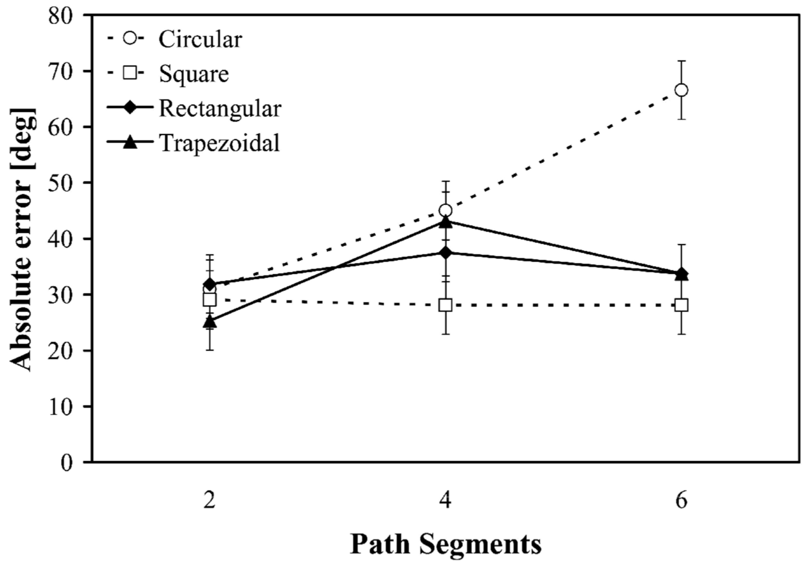

Figure 3.
Absolute pointing error in Experiment 1 as a function of path length, plotted separately for the four environments. Error bars represent standard errors estimated from the ANOVA.

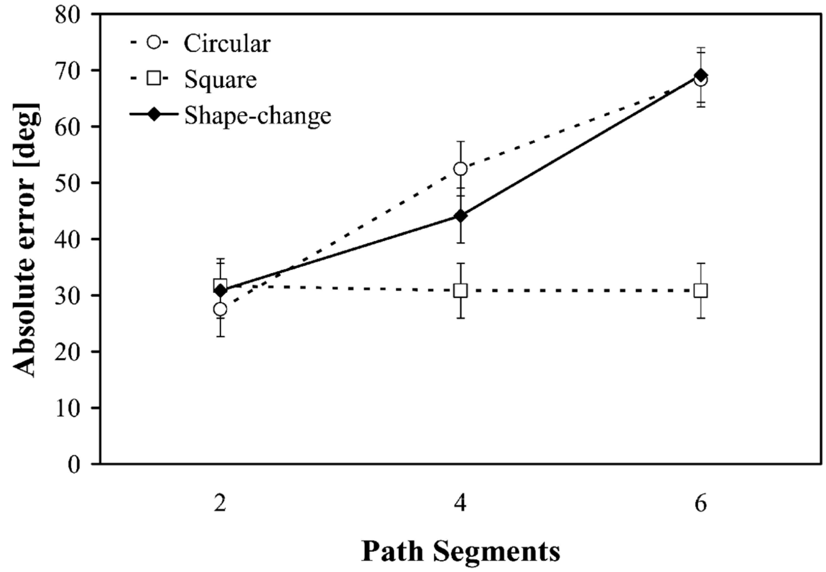

Figure 4.
Absolute pointing error in Experiment 2 as a function of path length, plotted separately for the three environments. Error bars represent standard errors estimated from the ANOVA.