Individual differences in using geometric and featural cues to maintain spatial orientation: Cue quantity and cue ambiguity are more important than cue type

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Two experiments explored the role of environmental cues in maintaining spatial orientation (sense of self-location and direction) during locomotion. Of particular interest was the importance of geometric cues (provided by environmental surfaces) and featural cues (nongeometric properties provided by striped walls) in maintaining spatial orientation. Participants performed a spatial updating task within virtual environments containing geometric or featural cues that were ambiguous or unambiguous indicators of self-location and direction. Cue type (geometric or featural) did not affect performance, but the number and ambiguity of environmental cues did. Gender differences, interpreted as a proxy for individual differences in spatial ability and/or experience, highlight the interaction between cue quantity and ambiguity. When environmental cues were ambiguous, men stayed oriented with either one or two cues, whereas women stayed oriented only with two. When environmental cues were unambiguous, women stayed oriented with one cue.

Successful navigation through a known environment requires an accurate sense of spatial orientation (defined herein as self-location and direction within the surrounding environment) before proceeding toward a goal. For example, a hiker returning home must identify his or her location and direction within the surrounding environment before determining in which direction to proceed. This sense of spatial orientation is informed by environmental cues and also by path integration: the process of integrating self-motion cues over time. These experiments explored the influence of environmental cues on spatial orientation, using a task that required combined use of environmental cues and path integration.

Spatial orientation can often be achieved by identifying environmental properties, such as a known building on campus, or a recognizable painting in a hallway, and matching those with the same properties in long-term spatial memory. Previous research distinguishes two types of environmental properties: geometric and featural cues. According to Gallistel (1990), geometric cues are defined by extended environmental surfaces, such as the shape formed by room walls or undulating terrain. Featural cues are non-

geometric cues, such as colors and smells, which cannot be defined by geometry alone. The roles of geometric and featural cues in spatial orientation were first examined by Cheng (1986), who investigated the reorientation behavior of rats. In Cheng's experiments, rats learned to locate food hidden in one corner of a rectangular enclosure. The correct corner was defined by the angle and ratio of connecting walls (geometric cue) and also by a uniquely colored and scented panel (featural cue). After learning, rats were disoriented (by briefly being transferred into a dark cage while the experimental enclosure was randomly rotated) and returned to the enclosure. During subsequent food searches, rats often committed rotational errors, searching in the corner diagonally opposite the correct corner. The diagonally opposite corner was geometrically identical to the correct corner but featurally distinct. These rotational errors show that rats used geometric cues and ignored featural cues when reorienting to the environment, indicating that the distinction between featural and geometric cues is behaviorally relevant (for a review, see Cheng & Newcombe, 2005).

Disorientation is often employed when environmental cues to spatial orientation are studied. However, disorien-

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tation eliminates other cues commonly available during navigation. Specifically, disorientation eliminates path integration, the process of integrating internal (vestibular and proprioceptive) and/or external (optic/acoustic flow) self-motion cues over time (Mittelstaedt, 1985). The importance of path integration becomes clear when one navigates through impoverished environments. For example, finding one's way to the kitchen in the dark without bumping into unseen obstacles requires path integration. Similarly, staying oriented while walking through an empty square room requires path integration. Even though geometric cues are visually available in this example, those cues are only ambiguous indicators of spatial orientation (the square room is fourfold rotationally symmetric, meaning there are four room orientations that could produce any perspective).

Experiments by Klatzky et al. (1990) explored the limits of human path-integration ability. In a spatial updating task, blindfolded participants walked along outbound paths while keeping track of a learned location (in this case, the path origin). Paths varied from 1–3 path segments, with each segment separated by a turn. Upon reaching the path terminus, participants attempted to point to the path origin, and errors increased with increasing path segments. Without stable environmental properties, errors in estimating spatial orientation steadily increased, underscoring the insufficiency of path integration over extended travel.

A growing body of evidence indicates that humans and other animals combine environmental cues with path integration to determine spatial orientation during navigation (Cheng, Shettleworth, Huttenlocher, & Rieser, 2007; Nardini, Jones, Bedford, & Braddick, 2008). The primary goal of the present study was to identify the relevant environmental cues used by adults to maintain spatial orientation during locomotion. There is no a priori reason that environmental cues should play a different role in maintenance of orientation than in reorientation. In these experiments, we chose a navigation task in which spatial orientation could only be achieved by combining environmental cues and path integration. These experiments focus on the following environmental cue types: (1) diffuse geometric cues defined by extended surfaces; (2) localized geometric cues defined by vertices at surface intersections; and (3) localized featural cues. The distinction between diffuse and localized geometric cues is supported by work showing that children reorient using surfaces but not corners

(Gouteux & Spelke, 2001). Unlike localized geometric cues, localized featural cues do not define the boundaries of the surrounding space.

These experiments were conducted using immersive virtual reality, which represents a unique tool for presenting environmental cues that would otherwise be difficult to manipulate. Participants in these experiments explored virtual environments by physically walking and turning, just as in the real world. Although distances in virtual environments are commonly underestimated (Loomis & Knapp, 2003), spatial memories of virtual environments adhere to the same organizational principles as do memories of real environments (Kelly, Avraamides, & Loomis, 2007; Kelly & McNamara, 2008).

EXPERIMENT 1

Experiment 1 explored the roles of different environmental cue types in maintenance of spatial orientation. In all cases, environmental cues were ambiguous indicators of spatial orientation. Participants performed a spatial updating task (similar to that used by Klatzky et al., 1990) that required keeping track of a learned location while walking along paths varying in number of path segments, where each segment was separated by a turn. The task was performed in four virtual rooms (Figure 1). First, to determine baseline performance when spatial orientation could only be known through path integration, a circular room was used, in which performance should degrade with increasing path segments. Second, a square room defined by surfaces and corners was used to determine performance when two geometric cue types were available. Using a similar square room, Kelly, McNamara, Bodenheimer, Carr, and Rieser (2008) found that participants successfully combined path integration with the two geometric cue types, and that performance was unaffected by path segments. Therefore, the square room should provide an estimate of maximal performance. Third, a square room in which the corners were removed (by removing the outer 14% of each wall) was used to determine whether spatial orientation could be maintained using surfaces only. Finally, a circular room with four identical vertical stripes painted on the walls was used to determine whether spatial orientation could be maintained using localized features only. Vertical stripes were chosen for their similarity to corners of a square room, because both have the same spatial arrangement and both are localized cues, unlike

Circular room   Circular room with stripes   Square room   Square room without corners
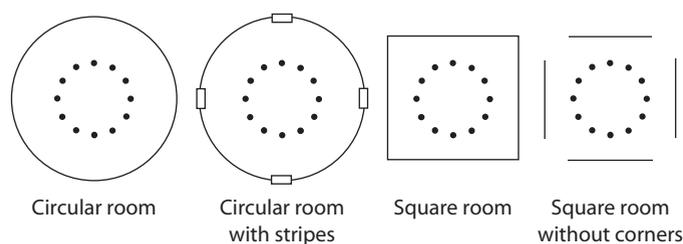
Figure 1. Plan view of the virtual rooms used in Experiment 1. Filled circles represent the post locations. In the circular room with stripes, the white boxes represent the locations of the vertical stripes on the wall.
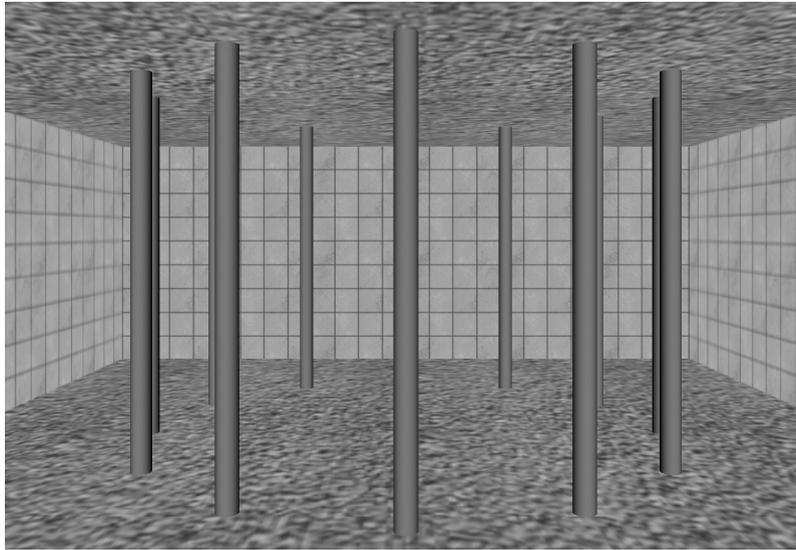
Figure 2. Perspective view of the square room from outside the circle of posts.

extended wall surfaces. Environmental cues in the square rooms with and without corners and the circular room with stripes were ambiguous (fourfold rotationally symmetric); successful spatial updating therefore required path integration in order to avoid confusing one's actual location and direction with the other three locations and directions that would provide the same view of the room.

Method

Participants. Sixteen men and 16 women from the Nashville community (average age, 20.6 years) participated in exchange for monetary compensation.

Stimuli and Design. Virtual environments were displayed on an nVisor SX head-mounted display (HMD; NVIS, Reston, VA) with a 60º diagonal field of view. Stereoscopic images were presented at 1,280 × 1,024 pixel resolution, refreshed at 60 Hz. 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. Head orientation was tracked by a 3-degrees-of-freedom orientation sensor (InertiaCube2; Intersense, Bedford, MA), and head position by a passive optical tracking system (PPTX4; WorldViz, Santa Barbara, CA). Graphics were updated on the basis of sensed head movement, such that physical translations and rotations caused concomitant visual movement through the virtual world.

On each trial, participants attempted to keep track of a learned location while walking along a path. Path segments and environment type were manipulated within participants. The walked path could be two, four, or six segments in length. The surrounding environment could be circular, square, square without corners, or circular with stripes. Environment type was blocked and order was counterbalanced using a balanced Latin square. Participants completed six trials within each environment, corresponding to two repetitions of three path lengths. Path length was randomized within blocks.

All virtual rooms were 2 m tall with a 21-m wall–surface perimeter. Both circular rooms were 6.68 m in diameter and both square rooms were 5.25 × 5.25 m. Walls were textured with a tile pattern (Figure 2). In the circular room with stripes, four vertical white stripes (20 cm wide, spaced every 90º) were overlaid on the tiles. In the square room without corners, the outer 75 cm (~14%) of each wall were removed (thereby removing room corners), and wall opacity increased from 0% to 100% over the next 50 cm of remaining surface. Thus, each wall became fully opaque at 125 cm, from where the walls would

have intersected. The gradual opacity change was intended to prevent participants from tracking surface discontinuities in lieu of corners. Outside all rooms was an infinite extension of the floor and ceiling, and visibility was obscured beyond 10 m by fog.

Within each virtual environment, 12 cylindrical posts were evenly spaced around a 3-m-diameter circle. Posts were 2 m tall and 10 cm in diameter, and the experimenter controlled their visibility and color.

Procedure. After donning the HMD, participants stood in the center of the virtual room and were instructed to visually inspect the virtual environment by rotating 360º prior to beginning the first trial. This visual inspection occurred upon first experiencing each environment. At the beginning of each trial, 1 of the 12 gray posts turned red and the remaining posts disappeared. Participants were told to remember the location of the red post. Participants then walked to the red post, which disappeared upon their arrival, and a green post then appeared at one of the remaining 11 locations. They then walked to the green post, which also disappeared upon arrival, and a second green post appeared from the remaining 10 locations. In this way, participants walked a path through the virtual environment, with each green post leading them along another path segment. Because the posts fit within the confines of the 5 × 5 m physical lab space, there was never any danger of running into lab walls. After reaching the final green post, the room walls disappeared and the 12 gray posts reappeared. Participants indicated the location of the red post by facing one of the gray posts and signaling that they had made their selection (facing direction was recorded using the VR equipment). Room walls were removed during response so that participants had to maintain spatial orientation during locomotion. If the walls had remained, participants in rooms containing environmental cues might have ignored the spatial updating task, since reorientation prior to response would have allowed for above-chance performance (particularly in Experiment 2, when environmental cues were unambiguous). After participants responded, the room walls reappeared, the red post appeared in a new location, and the next trial began. Participants never received feedback.

Results

Pointing error (Figure 3) was analyzed in a 2 (gender) × 3 (path segments) × 4 (environment) mixed-model ANOVA. Main effects of gender [$F(1,30) = 8.30$, $p = .007$, $\eta_p^2 = .22$], path segments [$F(2,60) = 24.83$, $p < .001$, $\eta_p^2 = .45$], and environment [$F(3,90) = 3.98$, $p < .01$, $\eta_p^2 = .12$] were qualified by a three-way interac-
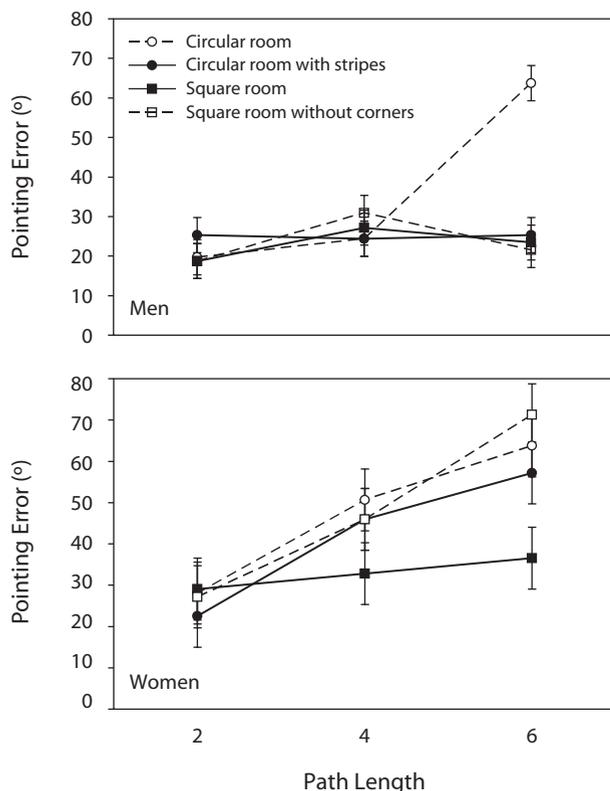
Figure 3. Mean absolute pointing errors in Experiment 1 as a function of walked path length, plotted separately for men (top) and women (bottom). Error bars represent standard errors estimated from the ANOVA.

tion [$F(6,180) = 3.34$, $p = .004$, $\eta_p^2 = .10$]. In the circular room, pointing errors increased as path segments increased from two to six, for both men [$F(1,15) = 28.39$, $p < .001$, $\eta_p^2 = .65$] and women [$F(1,15) = 8.69$, $p < .01$, $\eta_p^2 = .37$]. Interaction contrasts, conducted separately for men and women, identified the environments in which performance improved relative to baseline performance in the circular room. For men, performance in the square room, square room without corners, and circular room with stripes was less affected by increasing path segments (from two to six) when compared with performance in the circular room [square, $F(1,15) = 21.83$, $p < .001$, $\eta_p^2 = .59$; square without corners, $F(1,15) = 30.25$, $p = .004$, $\eta_p^2 = .43$; circular with stripes, $F(1,15) = 12.26$, $p = .003$, $\eta_p^2 = .45$]. For women, performance in the square room was less affected by increasing path segments (from two to six) when compared with performance in the circular room [$F(1,15) = 4.18$, $p = .059$, $\eta_p^2 = .22$], but performance in the circular room with stripes and the square room without corners was no different than in the circular room.

Discussion

The environments in Experiment 1 can be characterized by their number of available environmental cue types.[1] The circular room contained zero environmental cues—neither geometric nor featural. The circular room with stripes and the square room without corners each contained one cue

type, and the square room contained two cue types (both surfaces and corners). When zero environmental cues were available, errors committed by men and women increased with increasing path segments. This was expected because updating self-position and direction through path integration is noisy, and noise accumulates while one walks and turns (Klatzky et al., 1990). When two environmental cue types were available, men and women stayed oriented to the environment, and errors were unaffected by increasing path segments, replicating Kelly et al. (2008). Noisy estimates of self-location and direction from path integration may have been used to disambiguate the environmental cues. When only one environmental cue type was available, whether it was featural or geometric, men stayed oriented and women did not.

Gender differences in Experiment 1 might be due to underlying individual differences in spatial ability or experience, for which gender serves as a coarse measure. This conjecture is supported by findings that men rate themselves higher than women on sense of direction (SOD; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006), and that self-reported SOD correlates positively with spatial updating performance (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). This possibility is pursued further in the General Discussion.

Regardless of their origins, the gender differences found here diverge from previous findings that men use geometric or featural cues to determine spatial orientation, whereas women primarily use featural cues (Sandstrom, Kaufman, & Huettel, 1998). However, previous reports of gender differences in cue use have typically employed reorientation paradigms, whereas the present experiments require maintenance of orientation during locomotion. In one such reorientation experiment (Sandstrom et al., 1998), participants learned a goal location in a virtual environment containing featural and geometric cues. Participants later attempted to reorient and locate the goal in an environment containing one of the two cues available during learning. Women performed better with featural cues than with geometric cues, but men performed well with either cue type. However, Experiment 1 is not especially amenable to comparison with Sandstrom et al.'s experiment; not only were the tasks different (spatial updating vs. reorientation), but so was the quality of information carried by the environmental cues. Environmental cues in Experiment 1 were fourfold rotationally symmetric, and therefore only ambiguous indicators of spatial orientation. In contrast, environmental cues used by Sandstrom et al. were onefold rotationally symmetric (unambiguous). Experiment 2 explored the possibility that women would stay oriented with a single unambiguous environmental cue.

EXPERIMENT 2

Two new virtual environments were created in which either featural or geometric cues unambiguously specified spatial orientation within the room (Figure 4). The first new environment was a circular room with four uniquely colored stripes. The second was a kite-shaped room without corners, leaving the shape defined only by environ-
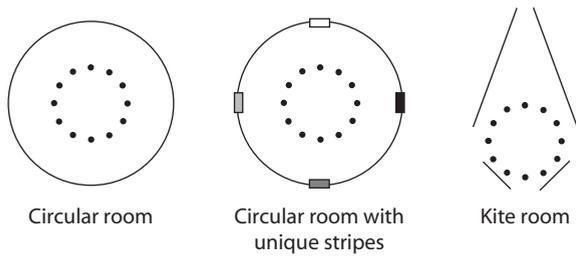
Figure 4. Plan view of the virtual rooms used in Experiment 2. Filled circles represent the post locations. In the circular room with unique stripes, the boxes represent the locations of uniquely colored vertical stripes on the wall.

Circular room   Circular room with unique stripes   Kite room

mental surfaces. Because men in Experiment 1 stayed oriented using ambiguous cues, it was assumed they would stay oriented using unambiguous cues, so only women were tested.
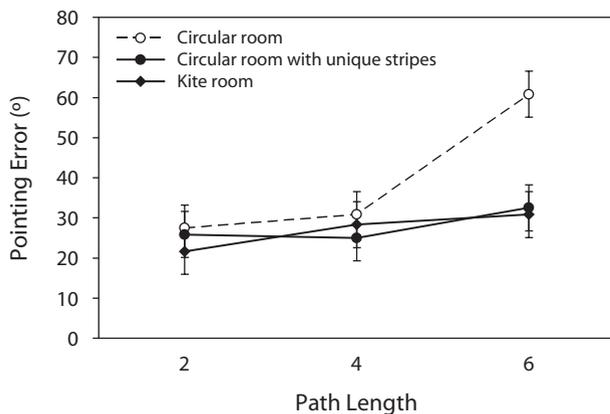
Method

Participants. Eighteen women from the Nashville community (average age, 21.7 years) participated in exchange for monetary compensation.

Stimuli, Design, and Procedure. The virtual environments were circular, circular with unambiguous stripes, or kite-shaped without corners. The circular room with unambiguous stripes included four uniquely colored stripes (white, blue, black, and yellow) on the wall, spaced every 90°. The kite room comprised four walls—two 7-m walls and two 3.5-m walls—and the room corners were removed using the same method as before. The design and procedures were identical to those used in Experiment 1.

Results

Pointing error (Figure 5) was analyzed in a 3 (path segments) × 3 (environment) repeated measures ANOVA. Main effects of path segments [$F(2,34) = 6.48, p = .004, \eta_p^2 = .28$] and environment [$F(2,34) = 5.35, p = .01, \eta_p^2 = .24$] were qualified by a two-way interaction [$F(4,68) = 2.65, p = .04, \eta_p^2 = .14$]. In the circular room, pointing errors increased as path segments increased from two to six [$F(1,17) = 15.32, p = .001, \eta_p^2 = .47$]. Interaction con-

trasts showed that performance in the circular room with stripes and the kite room was less affected by increasing path segments than was performance in the circular room [circular with stripes, $F(1,17) = 5.52, p = .031, \eta_p^2 = .25$; kite, $F(1,17) = 8.41, p = .01, \eta_p^2 = .33$].

Discussion

Women stayed oriented using unambiguous features or unambiguous geometry, even though only one cue type was available in each environment. As in Experiment 1, there was no effect of cue type. This result is inconsistent with findings of Sandstrom et al. (1998), who concluded that women reorient using unambiguous features but not unambiguous geometry. However, reorientation might draw on environmental cues differently than the spatial updating task used here. Additionally, their findings might represent gender differences in cue salience rather than in ability to use specific cues. In Sandstrom et al.'s experiment, geometric and featural cues were both available during learning. For women (but not men), the geometric cues may have been overshadowed by the featural cues. As such, Sandstrom et al.'s findings might reflect gender differences in cue overshadowing rather than ability to use those cues. Others have used cue salience to explain why cue use is modulated by environment size (Ratliff & Newcombe, in press).

GENERAL DISCUSSION

These experiments sought to identify the relative roles of two types of environmental cues—geometric and featural cues—using a spatial updating task in which successful performance relied on maintaining spatial orientation during locomotion. Cue type did not affect spatial updating performance; no differences were found between environments containing geometric or featural cues, consistent with experiments showing that adults use both cue types similarly during reorientation (Gouteux & Spelke, 2001; Hermer & Spelke, 1994). However, cue quantity and cue ambiguity both influenced performance and revealed large individual differences. Women in Experiment 1 did not stay oriented while locomoting in environments with one ambiguous environmental cue type, but they did stay oriented with two ambiguous environmental cue types. In contrast, men stayed oriented with one ambiguous environmental cue type. The cue quantity effect might be due to cue salience (two cue types are more salient than one), but it is unclear why salience would affect men and women differently. Women in Experiment 2 stayed oriented with one unambiguous cue type.

To stay oriented within ambiguous environments (like the square room in Experiment 1), we believe that participants used path integration to disambiguate environmental cues. For example, facing the center of a wall within the square room indicates possible self-orientations of 0°, 90°, 180°, or 270°. However, if path integration indicates self-orientation of 70°–110° (but noise prevents a more accurate estimate), these two sources can be combined to determine that 90° is the current facing direction. In other words, noisy estimates from path integration can be used to disambigu-

Figure 5. Absolute pointing errors made by women in Experiment 2, plotted as a function of walked path length. Error bars represent standard errors estimated from the ANOVA.

ate environmental cues, and staying oriented within ambiguous environments (Experiment 1) required incorporation of path integration and environmental cues. This does not necessarily pertain to Experiment 2, where environmental cues alone unambiguously indicated spatial orientation.

The gender differences found here are inconsistent with previous reports indicating that women use featural cues, but not geometric cues, to reorient (Sandstrom et al., 1998). This inconsistency might be due to differences in stimuli. Previous reports of individual differences in cue use have employed environments containing both featural and geometric cues, and individual differences might reflect differences in cue salience. The present experiments used environments containing *only* geometric or featural cues, and participants did not have a choice of cue type.

Previous work on individual differences indicates that gender serves as a proxy for a multitude of differences in spatial abilities (Linn & Petersen, 1985). Men typically rate themselves higher on SOD scales (Hegarty et al., 2006), and self-reported SOD correlates positively with spatial updating performance (Hegarty et al., 2002). It is possible that men and women in our experiments represent a rough categorization of high and low SOD. Under this interpretation, people with low SOD require more environmental cues to stay oriented than people with high SOD. Additionally, men commonly report having more video game experience than women (Terlecki, Newcombe, & Little, 2008), and this difference could lead to performance differences in two ways. First, computer-generated virtual environments bear close resemblance to video game environments, and experienced gamers might be more comfortable and less distracted by virtual environments. Second, video game training transfers to performance on small-scale spatial tasks such as mental rotation (Terlecki et al., 2008), so experienced gamers may have superior spatial skills, which transfer to the spatial updating task. One implication is that increased training and feedback could selectively improve women's spatial updating performance.

These experiments indicate that quantity and ambiguity of environmental cues influence maintenance of spatial orientation during locomotion, and these effects interact with individual differences in spatial ability and/or experience. These experiments also supplement existing evidence that featural and geometric cues play similar roles in supporting spatial orientation, and extend those findings from reorientation to maintenance of orientation, a more complex task requiring the combination of environmental and path integration cues.

AUTHOR NOTE

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NOTE

1. This analysis focuses on number of environmental cue types, where each cue type was represented by four cue elements (stripes are one cue type, even though there were four stripes).