

Journal of Experimental Psychology: Learning, Memory, and Cognition

The World Is Not Flat: Can People Reorient Using Slope?

Daniele Nardi, Nora S. Newcombe, and Thomas F. Shipley

Online First Publication, December 20, 2010. doi: 10.1037/a0021614

CITATION

Nardi, D., Newcombe, N. S., & Shipley, T. F. (2010, December 20). The World Is Not Flat: Can People Reorient Using Slope?. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. Advance online publication. doi: 10.1037/a0021614

The World Is Not Flat: Can People Reorient Using Slope?

Daniele Nardi, Nora S. Newcombe, and Thomas F. Shipley
Temple University

Studies of spatial representation generally focus on flat environments and visual input. However, the world is not flat, and slopes are part of most natural environments. In a series of 4 experiments, we examined whether humans can use a slope as a source of allocentric, directional information for reorientation. A target was hidden in a corner of a square, featureless enclosure tilted at a 5° angle. Finding it required using the vestibular, kinesthetic, and visual cues associated with the slope gradient. In Experiment 1, the overall sample performed above chance, showing that slope is sufficient for reorientation in a real environment. However, a sex difference emerged; men outperformed women by 1.4 SDs because they were more likely to use a slope-based strategy. In Experiment 2, attention was drawn to the slope, and participants were prompted to rely on it to solve the task; however, men still outperformed women, indicating a greater ability to use slope. In Experiment 3, we excluded the possibility that women's disadvantage was due to wearing heeled footwear. In Experiment 4, women required more time than men to identify the uphill direction of the slope gradient; this suggests that, in a bottom-up fashion, a perceptual or attentional difficulty underlies women's disadvantage in the ability to use slope and their decreased reliance on this cue. Overall, a bi-coordinate representation was used to find the goal: The target was encoded primarily with respect to the vertical axis and secondarily with respect to the orthogonal axis of the slope.

Keywords: spatial abilities, reorientation, vertical dimension, slope or geographical slant, sex differences

All of us have experienced the uncomfortable feeling of being lost. Coming out from the subway; waking up in a dark, unfamiliar room; or coming out from an elevator in a large, multilevel parking lot; we may feel that we have lost track of where we are. However, as soon as we recognize a key aspect of the environment (e.g., a sign, a distinctive building), we are usually able to realize our position and facing direction. This process, called *reorientation*, is an essential ability for any mobile animal challenged with navigating and finding a goal.

There are many kinds of spatial cues that can plausibly be used for reorientation, including landmarks, sounds, magnetic fields, and odor gradients. However, most research attention has focused on visual cues and on the possibility that the reorientation process is selectively attuned to use the geometric shape of the environment (the *geometric module* hypothesis; Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1994, 1996; Wang & Spelke, 2002). In particular, the bulk of the reorientation literature on human and nonhuman animals has investigated the use of the geometric information provided by a layout of walls of an enclosure, and to

what extent other visual feature cues, such as landmarks and beacons, can be combined with geometry (recent reviews: Cheng, 2008; Cheng & Newcombe, 2005; Twyman & Newcombe, 2010).

One spatial cue that has been neglected is the three-dimensional topography of the land. In fact, most of the research on spatial cognition is carried out on completely horizontal surfaces. However, the world is not flat, and we naturally move on surfaces of varying elevation. Thus, it is crucial to examine how space is represented in vertically extended environments, such as hills, dunes, and mountains. Vertical topography is a salient spatial cue for three main reasons. First, these terrain features are stable and not likely to change over time, at least not in the short term, as emphasized for geometry cues by Gallistel (1990). Other features of the environment may change over the course of a day (celestial cues covered by clouds) or a season (leaves change color and fall from trees, ground can be covered by snow, rivers can dry out in summer). Because of its permanent nature, three-dimensional topography is a very reliable source of spatial information for navigating and determining a goal location (nest, food sources). Furthermore, navigable surfaces extended in the vertical dimension are salient because movements with a vertical component are generally more effortful compared with movements on a horizontal, flat plane. The energy demand associated with counteracting the force of gravity renders the vertical dimension of space cognitively salient for the whole animal kingdom, from bees (the symbolic use of the vertical axis in the waggle dance; Von Frisch, 1967) to humans (the privileged role of the vertical axis for spatial reference frames; Carlson & Van Deman, 2008; Franklin & Tversky, 1990). Finally, hills, dunes, and mountains not only can be seen but they can also be felt by kinesthetic and vestibular senses when navigating on them. Therefore, compared with landmarks and geometry, vertically extended surfaces provide a navigator

Daniele Nardi, Nora S. Newcombe, and Thomas F. Shipley, Spatial Intelligence and Learning Center, Department of Psychology, Temple University.

This research was supported by National Science Foundation Grant SBE-0541957 to the Spatial Intelligence and Learning Center, for which we are very grateful. We thank Amanda Y. Funk for her help collecting data.

Correspondence concerning this article should be addressed to Daniele Nardi, Department of Psychology, Temple University, 1701 North 13th Street, Philadelphia, PA 19122. E-mail: daniele@temple.edu

with a complex of multimodal cues, and this potential sensory redundancy renders vertical topography a uniquely salient cue.

The simplest surface extended in the vertical dimension is a terrain slope (also called a geographical slant; Durgin, Hajnal, Li, Tonge, & Stigliani, 2010; Proffitt, Bhalla, Gossweiler, & Midgett, 1995). A slope provides an allocentric, directional source of information that can be used for reorientation and goal location. In fact, a navigator walking on a tilted surface can reference bearings extracted from the slope gradient, such as the uphill, the downhill, or any direction in between. For instance, if you parked your car on a hill, you can find it by remembering the direction (azimuth) you have to walk with respect to the slope (e.g., walk uphill and go slightly left). In this sense, slope is similar to a distant landmark (e.g., a mountain in the horizon), which is too far away to be used for estimating small-scale distances—and thus does not provide positional information—but can still provide a directional reference frame (e.g., to find the car, walk straight keeping the mountain on your left; Jacobs & Schenk, 2003). Furthermore, with respect to the geometry/nongeometry dichotomy, slope can be considered a nongeometric (or feature) cue because it is not dependent on the relationship between points and points, or surfaces and surfaces, in the environment (Gallistel, 1990). Slope is a property solely determined by the inclination of the navigable surface relative to the force of gravity; thus, it can be defined as a gravity-dependent, feature cue. Studies on the neurological underpinnings of spatial representations seem to corroborate this definition. Using functional magnetic resonance imaging, it has been shown that the hippocampus and neighboring regions are centrally involved in the phenomenon of reorientation (Sutton, Joannis, & Newcombe, 2010); in accord with this finding, an intact hippocampus is required for encoding a geometry-based goal representation (McGregor, Hayward, Pearce, & Good, 2004; Vargas, Petruso, & Bingman, 2004). However, a slope representation can be acquired even following hippocampal lesions (Nardi & Bingman, 2009b), as is the case with other feature-based representations (Hampton & Shettleworth, 1996; Strasser & Bingman, 1997).

In a natural environment, a slope can be perceived statically and dynamically by multiple sensory modalities: by the sense of balance (vestibular cues), by the angles of the joints, and by muscular effort (kinesthetic cues). In addition, a slope can be sensed visually; because trees and walls of buildings are aligned with the gravity axis, the angle of incidence between them and the slanted ground is acute on one side and is obtuse on the other side. Any of these slope-associated cues (vestibular, kinesthetic, and visual) is theoretically sufficient to determine the presence of a slope; we refer to this multimodal complex collectively as *slope cues* or *slope information*.

To date, reorientation by slope has been studied mostly in rats (Miniaci, Scotto, & Bures, 1999) and pigeons (Nardi & Bingman, 2009a). Animals learned to localize a food reward among a square array of four potential hiding places on a sloped surface. Because the testing arena was completely featureless, and because subjects were disoriented before each trial, the only cue that polarized the environment and that could be used to pin-point the correct location was the slope. Results from pigeons revealed that a bi-coordinate, slope representation was used: The goal was encoded on the basis of its position along the vertical (uphill-downhill) and orthogonal (left-right) axes of the slope (Nardi & Bingman, 2009a). Furthermore, it has been shown that this representation is

much more salient than a goal representation based on the shape of the environment (geometric information), even when slope is not as informative as geometry (Nardi, Nitsch, & Bingman, 2010).

In humans, the literature on slope has mainly focused on the phenomenon of perceptual overestimation of hill slant (see Durgin et al., 2010; Proffitt et al., 1995). Only two studies have dealt with the issue of reorientation and navigation. One study showed that navigation abilities in a computer-based, virtual town were improved when the environment was on a slant compared with a flat condition (Restat, Steck, Mochntzki, & Mallot, 2004). In another study, directional cues—including terrain slope—could be used to locate a goal in a virtual environment (Chai & Jacobs, 2009). However, no research to date has examined whether humans can reorient simply by using a tilted surface, and whether they can do so in a real environment. The difference between virtual and real environments is critical, as slope is a multimodal cue and thus cannot be fully represented by visual stimuli on a computer monitor. Thus, in view of the overall lack of research on spatial cues other than visual ones, and given the ecological relevance of slope, the first purpose of this study was to investigate the simple but crucial question of whether humans are able to reorient by slope.

A second purpose of the present study was to examine whether sex differences would apply also to the use of slope. An interesting aspect of human spatial abilities is that they sometimes exhibit remarkable differences between the sexes. Men tend to outperform women in psychometric tests of mental rotation and spatial perception (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). Furthermore, a male advantage has been shown in reorientation by geometric cues in a virtual environment (Kelly & Bischof, 2005), and, when way-finding or navigation abilities are measured, sex differences appear in real-world environments (Ishikawa & Montello, 2006; Lawton, Charleston, & Zieles, 1996; Saucier et al., 2002; Schinazi, Epstein, Nardi, Newcombe, & Shipley, 2009), in virtual environments (Astur, Ortiz, & Sutherland, 1998; Lawton & Morrin, 1999; Moffat, Hampson, & Hatzipantelis, 1998; Sandstrom, Kaufman, & Huettel, 1998), in self-reports (Dabbs, Chang, Strong, & Milun, 1998; Lawton, 1994), and in giving directions (Devlin, 2003; Ward, Newcombe, & Overton, 1986). Overall, this literature has often been interpreted as indicating sex-specific strategy use. Men are thought to rely more on global, metric, map-like information, and women are thought to rely more on landmark or route knowledge (Galea & Kimura, 1993; Lawton, 1994; Saucier et al., 2002; Ward et al., 1986). Similarly, it has been proposed that men make more use of directional types of cues (cardinal directions, gradients, distant landmarks), whereas women employ more positional cues (local landmarks; Jacobs & Schenk, 2003).

According to Jacobs and Schenk's (2003) interpretation, because slope is a gradient, directional type of cue, it would be expected that men outperform women. However, as mentioned above, most of the literature on reorientation—and on spatial abilities in general—has focused on purely visual stimuli. Indeed, a large chunk of the research on spatial cognition uses virtual, computer-simulated environments that provide solely visual information to participants. When spatial abilities are tested with non-visual tasks, converging evidence indicates a lack of sex differences. Studies have shown that, using haptic instead of visual stimuli, the typical male superiority in the Water-Level test (Berthiaume, Robert, St-Onge, & Pelletier, 1993) and in tests of

field independence (Walker, 1972) is eliminated. Similarly, women's greater overestimation of hill slants is eliminated under haptic conditions (Proffitt et al., 1995). Furthermore, it has been shown that, in a tactual spatial finger-maze task, women perform equally to (Alvis, Ward, & Dodson, 1989) or better than (Biersner, 1980) men, and that, in a kinesthetic acuity task, men outperform women only if visual cues are added (Livesey & Intili, 1996). Finally, studies on samples of sighted blindfolded and blind participants show no sex differences in way finding (Passini, Proulx, & Rainville, 1990) or mental rotation (Marmor & Zaback, 1976). One interpretation of these data is that men might have an advantage with visuo-spatial tasks but not with spatial tasks per se (Naylor & McBeath, 2008). If this hypothesis is correct, sex differences would not be expected because slope information is not primarily visual but also provides crucial vestibular and kinesthetic stimuli.

Experiment 1

To investigate whether humans are able to use slope information for reorientation, we used a goal location task. Participants had to find a target hidden in a corner of a square enclosure after having lost their sense of orientation by spinning on a swivel chair (see Figure 1A). No informative visual features were present in the enclosure. Furthermore, the configurational symmetry of the enclosure left a geometric ambiguity among all four corners. Therefore, neither egocentric (path integration), nor visual feature, nor geometric cues could be used to distinguish the goal from the other corners. However, because the enclosure was tilted, the slope gradient provided an allocentric, polarizing cue that could be used for reorientation and for locating the goal. To succeed in the task, participants simply had to reorient with respect to a reference direction extracted from the slope and use it to encode the goal corner. Following the example in Figure 2, and considering directions with respect to slope alike cardinal directions, the goal could

be encoded, for example, as being in the northwest corner (45° counterclockwise from the uphill—or north—direction).

In the experimental enclosure, the slope could be perceived by the same complex of cues that can be used in a natural environment. Vestibular and kinesthetic cues could be obtained from standing and walking on the slanted floor. Furthermore, because the walls of the enclosure (sheets) were vertical, the angle of incidence between the floor and the walls was different between the uphill side and downhill side of the enclosure: Uphill the angle was slightly obtuse, whereas downhill it was slightly acute (see Figure 1B). Therefore, when the enclosure was slanted, slope-associated visual cues were also available.

The angle of inclination used for the enclosure throughout the whole study was 5° . This is a very common inclination used for wheelchair ramps, and it was chosen for two reasons. First, it is readily perceived by people—pilot experiments showed that participants could easily identify the vertical axis of the slope even with just half of that inclination (2.5°). Second, a 5° inclination does not impose substantial difficulties of locomotion, and it does not convey any danger of falling (Nashner, 1983).

Participants had to locate the target for four training trials. Following a reference memory paradigm, the target was always hidden in the same corner relative to the slope gradient (e.g., always uphill on the left). After training, two test trials were carried out to ensure that participants could only use slope cues to solve the task.

Method

Apparatus. The experimental enclosure was placed inside an experimental room that measured 290×460 cm and that was 250 cm high. The size of the enclosure was 244×244 cm and was 203 cm high. The floor of the enclosure consisted of a wooden platform (244×244 cm, 12 cm thick) covered by gray carpet. White sheets

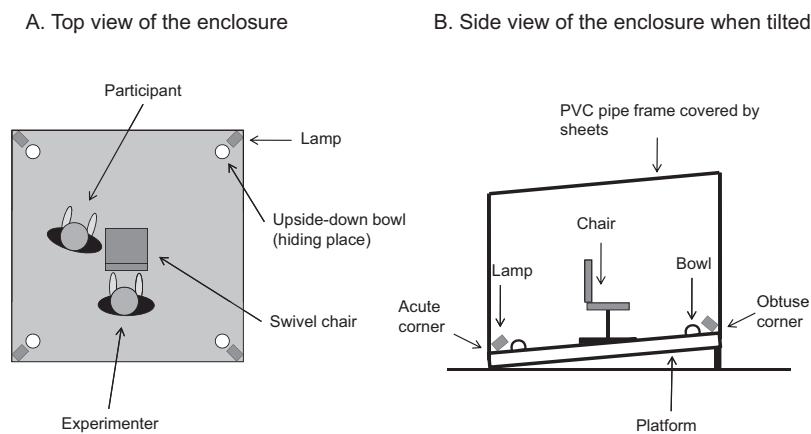


Figure 1. Schematic representation of the experimental enclosure used throughout the whole study. (A) The enclosure viewed from above. (B) The enclosure viewed from the side when tilted. Because the walls of the enclosure (sheets) were vertical, the angle of incidence between the walls and the tilted floor was slightly acute in the downhill side and was slightly obtuse in the uphill side of the enclosure. Throughout the whole study, participants were led by the experimenter into the enclosure always from the side that was propped up to render the enclosure tilted. Therefore, stepping on the platform, the step was higher when the enclosure was tilted than when it was flat. Participants also left the enclosure from that same side.

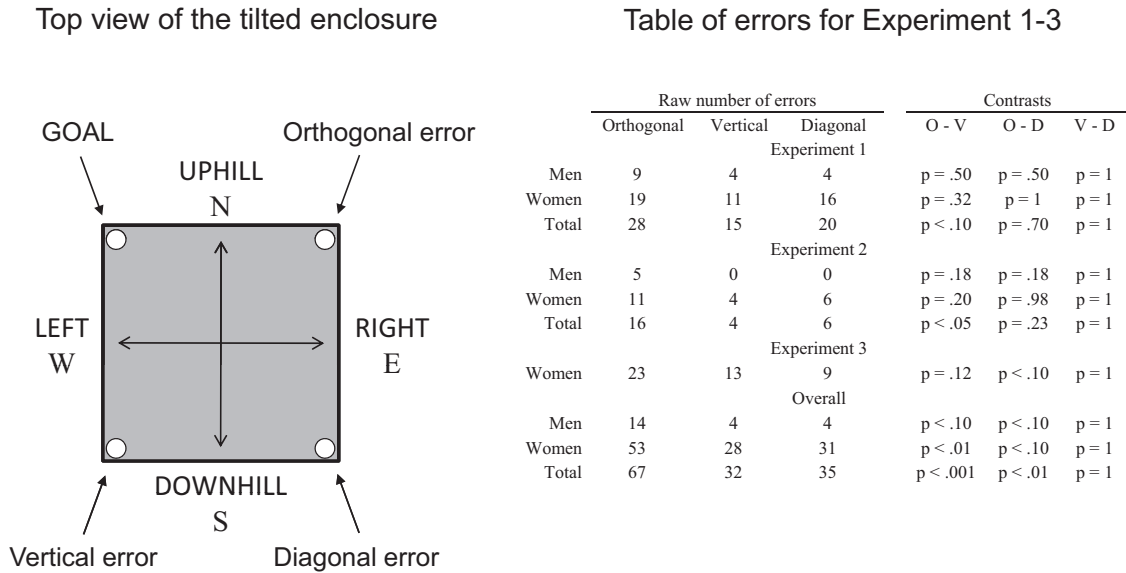


Figure 2. Analysis of errors committed during the (training) trials in Experiments 1–3. On the left-hand side, a schematic representation of the enclosure viewed from above is presented. The goal is represented in the corner uphill on the left (northwest corner); however, the goal location with respect to the slope gradient was counterbalanced across corners for each sex. *Orthogonal error* (uphill on the right) indicates a search at the corner with a correct vertical (uphill-downhill) but with an incorrect orthogonal (left-right) coordinate. *Vertical error* (downhill on the left) indicates a search at the corner with a correct orthogonal but with an incorrect vertical coordinate. *Diagonal error* (downhill on the right) indicates a search at the corner with both an incorrect vertical and orthogonal coordinate. On the right-hand side, a table of the raw number of errors committed during the (training) trials in Experiments 1–3 is presented, including data aggregated across experiments. Overall, half of the incorrect searches were orthogonal errors, and the other half were divided approximately equally between vertical and diagonal errors. Incorrect searches by each participant were analyzed with Wilcoxon signed-rank tests on each pair of incorrect corners (O-V: orthogonal vs. vertical; O-D: orthogonal vs. diagonal; V-D: vertical vs. diagonal). The p values in the three rightmost columns represent the probability of each contrast deviating from chance (p values have been corrected for multiple comparisons with Bonferroni’s adjustment). Considering the aggregated data, orthogonal errors were committed significantly more than vertical ($p < .001$) and diagonal ($p < .01$) errors; the frequency of vertical and diagonal errors was not different ($p = 1$). This trend is consistent—albeit not always statistically significant—even when errors are broken down by experiment and by sex. Orthogonal errors are consistently the most frequent, and the difference between vertical and diagonal errors never approaches significance.

on a PVC pipe frame composed the walls and the ceiling of the enclosure (see Figure 1). The enclosure could be placed horizontally on the ground or could be tilted by raising one side of the platform on wooden blocks through a lever. On the floor of the enclosure, in each corner, there was a 25-watt lamp (approximate dimensions: 11 × 11 cm, 18 cm high) and a red bowl placed upside-down (16 cm in diameter, 8 cm deep), which constituted the hiding place for the target. A swivel chair was placed in the center of the enclosure (base: 56 cm of diameter; total height: 110 cm). When the enclosure was slanted, a wedge was placed under the chair such that the chair’s axis of rotation was always parallel to the force of gravity. The bottom of the chair was covered with a square piece of white cloth (61 × 61 cm) that covered the legs of the chair and the wedge. It is important to note that, when spinning on the swivel chair, the participants’ feet never touched the floor, so no cues were available for keeping track of their position relative to the slope.

Participants. Participants were 20 male and 20 female Temple University undergraduate students, between 18 and 30 years of

age, who volunteered as a means of fulfilling course requirements. The sample was 47.5% Caucasian, 22.5% African American, 20% Asian, 5% Hispanic, 2.5% of other minorities, and 2.5% undeclared. The average age was 21.2 years for men ($SD = 2.31$) and 19.8 years for women ($SD = 1.12$). Participants signed up for the experiment through a website, on which they were told to wear comfortable shoes and that heels were not recommended. In case a participant wore heels or uncomfortable footwear, disposable paper slippers would be provided; however, this was never necessary. Before starting the experiment, participants signed the consent form and were briefed about the procedure. They were told that a target would be hidden and that they would have to try to find it after having been spun on a swivel chair. Thirty randomly assigned participants were tested by a male experimenter; 10 participants were tested by a female experimenter.

Training. In this phase, the enclosure was tilted at an inclination of 5°. To cover possible noise from outside the room and to prevent the use of any auditory cue, the participant listened to music through earphones for the whole duration of the experiment.

The volume was set very low, such that the instructions from the experimenter could be easily heard. Before entering the room, the participant wore a blindfold. Then, he/she was led by the experimenter inside the room and inside the enclosure. In this experiment (and throughout the whole study), because of space constraints in the experimental room, participants were led into the enclosure always from the same side—the side that was propped up to render the enclosure tilted. Therefore, entering the enclosure, the step was higher when the enclosure was tilted than when it was flat (see Figure 1B). Once inside the enclosure, the participant sat on the swivel chair and was spun for a few seconds to make him/her lose track of where he/she entered from. Then the participant took off the blindfold and was asked to walk around the enclosure to get acquainted with it. After this, the trial began. The experimenter showed the target (a \$1 bill) and hid it under one of the bowls. When ready, the participant sat on the chair, put the blindfold on and was spun for a few seconds. At this point there was a pause during which the participant sat blindfolded on the chair. The experimenter used this time to move the sheets that composed the walls of the enclosure (each sheet was moved to the adjacent side, clockwise) and to readjust the cloth under the chair in case it had been moved by the participant's feet. This procedure was carried out to make sure that participants could not use uncontrolled features (wrinkles, creases) on the sheets or on the cloth under the chair to remember the goal location. After this pause, the participant was spun again for about 1 min, varying direction and speed of rotation. Then he/she took off the blindfold, and the experimenter said "can you tell me where I hid the target?" The participant was instructed to get up, walk to a chosen bowl, and uncover it to see whether the target was there. No verbal feedback was given, but if the choice was wrong, the experimenter uncovered the correct bowl and showed the target. This trial was repeated three more times (a total of four training trials), with the target always in the same corner. In each trial, the participant started facing a different side of the enclosure (in counterbalanced order across each sex), and the experimenter always stood at the back of the chair. The location of the target with respect to the slope gradient was counterbalanced across corners for each sex. The approximate time between encoding and retrieval in each trial was 5 min. At the end of the fourth trial, the participant was told "now you will leave the room, and when you come back the target will be in the same place." The participant left the enclosure (from the same side he/she entered) without a blindfold and waited outside the room.

Testing. Two test trials were carried out, in counterbalanced order across each sex. In each trial, participants entered the experimental enclosure in the same way as during training. After being spun on the swivel chair with the blindfold on, they took off the blindfold and were asked "where is the target?" They were instructed to stand up, walk to a bowl, and point to it. This time the participant was not allowed to uncover the chosen bowl (no feedback was given). The side faced at the beginning of each trial varied randomly and was counterbalanced between men and women. Before each test trial, the walls of the enclosure (sheets) were moved, and the cloth under the chair was readjusted (just like during training). Between the two test trials, the participant had to leave the room; the approximate waiting time between trials was 2 min. The two test trials were the flat test and the slope test.

Flat test. The enclosure was placed horizontally on the ground. In this condition, there was no cue that polarized the

symmetrical environment. If participants during training were using only slope cues to locate the goal, now that the environment was flat, they should not be able to distinguish among the four corners and, therefore, they should perform at chance (25% probability to choose the correct corner).

Slope test. The enclosure was slanted at an inclination of 5° (as in training). If, during training, participants were using slope cues to encode the goal location, now—in contrast to the flat test—we would expect their performance to be above chance (25%).

Once the two test trials were completed, in another room the participant took the Water-Level test (Piaget & Inhelder, 1956; we used the test devised by Liben, 1995) and reported what information was used to locate the target. Finally, the participant was debriefed about the purpose of the experiment.

Throughout the whole study, mean values are always reported ± 1 *SD*.

Results

Training trials. During the four training trials, the sample as a whole was able to choose the correct corner significantly above chance, $t(39) = 7.16, p < .001$. Although both men, $t(19) = 14.33, p < .001$, and women, $t(19) = 2.41, p < .05$, performed above chance, a substantial difference appeared when the data were compared between sexes. Male performance ranged from 50% to 100% correct trials, with a mean of $78.8\% \pm 16.77$. Conversely, women ranged from 0% to 100% correct trials, with four participants at floor level (0% correct trials), a total of nine participants not above chance (25% correct), and a mean performance of $42.5\% \pm 32.55$ correct trials. This difference between sexes is significant—*t* test for unequal variances, $t(38) = 4.43, p < .001$ —and the effect size is large ($d = 1.40$; see Figure 3).

Mean percentage of correct trials (\pm *SD*)

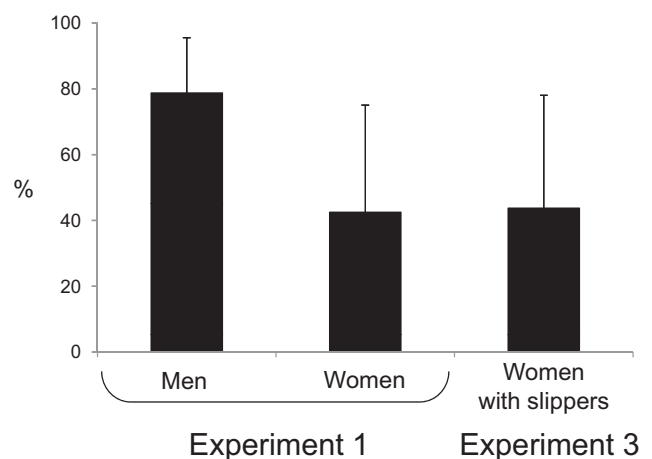


Figure 3. Mean percentage of correct trials (\pm *SD*) during training in Experiment 1 and in Experiment 3. In Experiment 1, men and women wore casual footwear, whereas in Experiment 3, women wore flat, paper slippers. Men performed significantly more correct trials than women with casual footwear or slippers. Women wearing casual footwear and paper slippers performed similarly.

Test trials. When tested on a flat surface (flat test), participants located the correct corner at a chance level (binomial test: men, $p = 1$; women, $p = .80$; see Figure 4A), showing that there were no uncontrolled cues in the enclosure that could be used for locating the goal and that the disorientation procedure was successful; the difference between sexes was not significant (Fisher's exact test, $p = 1$). However, when tested on the slope (slope test), both men and women performed significantly above chance (binomial test: men, $p < .001$; women, $p < .05$; see Figure 4A). This confirms the results of the training trials, which showed that both sexes could locate the goal using slope at a level above chance. More men (15 out of 20) than women (10 out of 20) chose correctly. Although this difference failed to reach statistical significance (Fisher's exact test, $p = .19$), it shows a trend in agreement with the training trials.

Self-reported strategy use. When asked at the end of the experiment, more men (18 out of 20) than women (nine out of 20) reported using slope to locate the target; this difference is significant (Fisher's exact test, $p < .01$; see Figure 4B). The two remaining men and seven women reported trying to keep track of how much they were spinning on the chair to remember the goal corner (path integration). Two women reported using the location of wrinkles, creases, and other details on the sheets or on the cloth under the chair. One woman reported using the light bulb filament of the lamp at the correct corner, and one woman was unable to report what information she used.

Water-Level test. Male scores in the Water-Level test were significantly higher than female scores, $t(38) = 2.13$, $p < .05$. There was a significant overall correlation between Water-Level test and percentage of correct training trials, $r(38) = .36$, $p < .05$. However, when controlling for sex, the correlation was not significant, $r(37) = .22$, $p = .18$. This suggests that Water-Level test and slope task performance correlated only because men are better than women in both tasks.

Discussion

This experiment shows, for the first time, that human adults can use terrain slope to reorient and locate a goal in a real-world

environment. Because of the geometric ambiguity of the square enclosure, the absence of visual features, and the disorientation procedure using the swivel chair, no cues were available to polarize the environment except for those associated with the floor being tilted. During training, both sexes chose the correct corner above chance. Furthermore, the combined results of the test trials rule out the possibility that participants were using cues other than the slope to solve the task. When the enclosure was flat, participants were disoriented and could not locate the goal above chance, whereas when the enclosure was slanted, they could reorient and successfully locate the target. It can be concluded that, for human adults, slope is a source of spatial information sufficient for regaining a sense of orientation and for identifying a goal location.

To find the target among the array of four symmetrical hiding locations, participants had to be able to perceive the slope gradient and to use a direction of reference to encode the goal location. Using a similar square arrangement of hiding places on a tilted, navigable surface, it has already been shown that rats (Miniaci et al., 1999) and pigeons (Nardi & Bingman, 2009a) can use the slope to reorient and locate a goal. Therefore, it was not unexpected that also human adults could succeed in such a task. However, surprisingly, a large sex difference emerged, with men outperforming women by 1.4 *SDs*.

Participants were not instructed as to what information to attend to, and they could have attempted to use non slope-associated cues to try to remember the target's location, such as relying on their internal sense of direction (path integration) or on uncontrolled details of the enclosure (sheets, cloth under chair). However, because measures were taken to render these alternative strategies ineffective (by spinning the participant on the chair and by moving the sheets and the cloth), the percentage of correct training trials offers an estimate of participants' reliance on the only cue that successfully and consistently predicted the goal location—slope. In this sense, it can be inferred that men had a greater disposition to rely on slope than women did. This is confirmed by participants' self-reported strategy use, according to which more men than women used slope cues to solve the task. It can be concluded that,



Figure 4. (A) Number of correct choices during the test trials in Experiment 1. When the enclosure was flat, both men and women performed at a level not different from chance. However, when the enclosure was sloped, both men and women chose the correct corner significantly above chance. (B) Self-reported strategy use in Experiment 1. At the end of the experiment, significantly more men than women reported using slope cues to solve the task.

although both sexes are able to use slope cues above chance, men have a greater propensity to rely on those cues.

Although women are less likely to use slope information, a different question would be: Is there a sex difference in the ability to use slope? Dimorphic strategies and dimorphic abilities are often confounded when it comes to sex differences in spatial cognition (Saucier et al., 2002). Men and women might have similar spatial abilities, and different performances might arise just because they use strategies that are not equally efficient for solving a task. In Experiment 1, women simply might have failed to notice that the floor was sloped, focusing more on visual details of the enclosure. It is possible that, if attention is drawn to the slope and participants are prompted to rely on it to solve the task, women would perform equally well as men. In other words, women could be less disposed, but not less able, to use slope for reorientation. The purpose of Experiment 2 was to examine this hypothesis.

Experiment 2

Experiment 2 was identical to Experiment 1, except for two points. First, because it was clear that only slope cues could be used to find the goal, the test trials were not included (only four training trials now). Second, an intervention procedure was added at the beginning of the experiment. To draw attention to the slope, a ball was shown rolling on the floor. Furthermore, the experimenter suggested that the slope should help in remembering the hiding place. With a clear demonstration that the floor is tilted and an explicit suggestion to rely on it to solve the task, Experiment 2 measured more specifically the ability—rather than the propensity—to use slope information.

Method

Twenty male and 20 female Temple University undergraduate students, between 18 and 30 years of age, participated in the experiment. The sample was 42.5% Caucasian, 27.5% African American, 12.5% Asian, 2.5% Hispanic, 7.5% of other minorities, and 7.5% undeclared. The average age of men was 22.4 ± 2.17 , and the average age of women was 21.1 ± 2.91 . None of the participants wore high heel shoes. The apparatus used was identical to Experiment 1. The experimental procedure consisted of the same four training trials as in Experiment 1 (i.e., participants had to find the target hidden in one of the four corners of the enclosure tilted by a 5° angle) except for the following difference.

In the first trial, before hiding the target under one of the bowls, the experimenter caught the attention of the participant and placed a colored ping-pong ball (4 cm of diameter) on the floor in the upper side of the enclosure. As the ball started rolling downhill, the experimenter said “this shows that the floor is tilted; the tilt should help you remember the hiding place.” After the ball rolled for approximately 150 cm, the experimenter picked up the ball.

At the end of the four trials, in another room the participant took the Water-Level test (Liben, 1995; Piaget & Inhelder, 1956) and reported what information was used to locate the target. Then the participant was debriefed about the purpose of the experiment. Thirty-five randomly assigned participants were tested by a male experimenter; five participants were tested by a female experimenter.

Results

Sex differences. During the four trials, both sexes chose the correct corner more than chance: men, $t(19) = 22.36$, $p < .001$; women, $t(19) = 6.43$, $p < .001$. However, there was again a marked difference in percentage of correct trials between the sexes. For the male sample, 16 participants were at ceiling (100% correct trials), and the mean performance was $93.8\% \pm 13.75$. Conversely, only 11 female participants were at ceiling, and the mean female performance was $73.8\% \pm 33.91$. This difference is statistically significant: t test for unequal variances, $t(38) = 2.44$, $p < .05$, $d = 0.77$ (see Figure 5). At the end of the experiment, all men and women reported using slope cues to locate the target.

In contrast with Experiment 1, male scores in the Water-Level test were not significantly different from female scores, $t(38) = 1.30$, $p = .20$. There was a significant correlation between Water-Level test and percentage of correct trials in the slope task, $r(38) = .56$, $p < .001$. Also, in contrast with Experiment 1, this correlation was significant even when controlling for sex, $r(37) = .53$, $p < .01$.

Effect of intervention. The effect of the intervention in Experiment 2 was examined by comparing performance with the four training trials of Experiment 1, the open task (see Figure 5). Women increased their performance by 74%, whereas men increased their performance only by 19%. However, the reduced improvement for men can be attributed to a ceiling effect. Nonetheless, when data are analyzed with a 2 (experiment) \times 2 (sex) between-subjects analysis of variance, there is a significant effect of experiment (higher performance in Experiment 2), $F(1, 76) = 15.97$, $MSE = 669.82$, $p < .001$, $\eta_p^2 = .17$, and a significant effect of sex (higher performance for men), $F(1, 76) = 23.62$, $p < .001$, $\eta_p^2 = .24$, but the interaction is not significant, $F(1, 76) = 1.97$, $p = .16$, $\eta_p^2 = .03$. This lack of interaction suggests that the sex gap did not significantly change in magnitude.

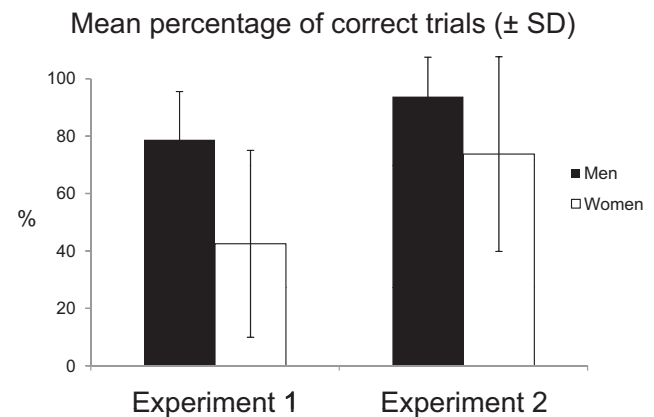


Figure 5. Mean percentage of correct trials (\pm SD) during training in Experiment 1 and in Experiment 2. Experiment 1 was an open task, and participants were not given suggestions as to which strategy to use to locate the goal. Conversely, in Experiment 2, attention was drawn to the slope, and participants were prompted to rely on it to solve the task. Just like in Experiment 1, in Experiment 2, men performed significantly more correct trials than women. Overall performance in Experiment 2 was significantly higher than in Experiment 1, and the Sex \times Experiment interaction was not significant.

Discussion

Self-reports confirmed that all participants at least attempted to use slope to locate the goal. Therefore, the intervention of showing the ball rolling and suggesting the slope strategy successfully convinced participants to rely on slope cues. Nonetheless, men still outperformed women. The sex difference apparently decreased relative to Experiment 1; however, comparing the magnitude of the sex difference is unwarranted because of a ceiling effect on men's performance in Experiment 2, and despite this limitation, the lack of an interaction did not support the idea that the sex difference was reliably lessened. It seems that a gap between the sexes exists not only in the propensity to rely on slope cues (as in Experiment 1) but also in the ability to use them, because men, when prompted, performed near ceiling, whereas women still had room for improvement.

Experiment 3

Experiment 2 ascertained that women were less skilled than men when using slope cues for reorientation and locating a goal. What are the factors behind this female disadvantage? In Experiment 3, we take into consideration the possibility that cultural differences with footwear might adversely affect women's performance in this task. Although participants did not wear high heels either in Experiment 1 or Experiment 2, women's casual footwear is generally much more likely to present a moderate heel compared with men. Walking on such heels could be considered somehow comparable with walking on an incline; therefore, it could be argued that women's everyday footwear introduce a bias in the perception of a sloped floor. This could reduce women's sensitivity to slope cues and impair their ability to use slope for reorientation. If women are disadvantaged because heels exert a negative effect on performance, then, when wearing completely flat footwear, their performance should improve.

In Experiment 3, women were tested in an identical task as in Experiment 1. However, this time they had to wear disposable paper slippers, which are completely flat. Performance was compared with Experiment 1, in which participants wore casual shoes, so that it was possible to test whether heels are responsible—at least in part—for the sex gap in reorientation by slope. If women are disadvantaged relative to men because of the heels associated with their casual footwear, their performance now should be higher with respect to that in Experiment 1.

Method

Twenty female Temple University undergraduate students, between 18 and 30 years of age, participated in the experiment. The sample was 45% Caucasian, 30% African American, 5% Asian, 5% Hispanic, 10% of other races, and 5% undeclared. The average age was 20.2 ± 2.65 .

The apparatus used was identical to Experiments 1 and 2. The experimental procedure consisted of the same four training trials as in Experiment 1. However, this time participants had to take off their shoes and were given disposable paper slippers (ScripHessco, Inc.) to wear during the whole experiment.

At the end of the experiment, participants took the Water-Level test and reported what information was used to locate the target.

Then participants were debriefed about the purpose of the experiment. All participants were tested by a male experimenter.

Results

Effect of female footwear. As a group, women chose the correct corner significantly more than chance, $t(19) = 2.45$, $p < .05$. Female performance with paper slippers paralleled that of women with casual shoes in the four trials of Experiment 1 (see Figure 3). The mean percentages of correct trials and the standard deviations were almost identical: 43.8 ± 34.29 with paper slippers, $42.5\% \pm 32.55$ with shoes (Experiment 1), $t(38) = 0.12$, $p = .91$. Furthermore, the number of participants at floor level of performance (0% correct trials: five with paper slippers, four with shoes), not above chance (25% or lower: nine with paper slippers, nine with shoes), and at ceiling level of performance (100% correct: two with paper slippers, three with shoes) was very similar. When compared with male performance in Experiment 1, women with paper slippers still performed a significantly lower percentage of correct trials: t test for unequal variances, $t(38) = 4.10$, $p < .001$, $d = 1.30$.

When asked at the end of the experiment, five women reported using slope cues to locate the target. The remaining participants reported using other, noneffective strategies: Eight participants tried to keep track of how much they were spinning on the chair (path integration); four participants used the location of wrinkles, creases, and other details on the sheets; two participants assumed the location of the goal was fixed with respect to them, as if they started each trial facing the same direction (egocentric encoding); and one participant used details on the cloth under the chair. The frequency of women who reported using slope cues is not significantly different when wearing paper slippers (five out of 20) and when wearing casual footwear (nine out of 20, Experiment 1; Fisher's exact test, $p = .32$). Furthermore, when wearing paper slippers—just like when wearing casual shoes—women reported using slope cues at a significantly lower frequency compared with men in Experiment 1 (18 out of 20; Fisher's exact test, $p < .001$).

Water-Level test. In agreement with data from Experiment 1, the correlation between Water-Level test and percentage of correct trials in the slope task was not significant, $r(18) = -.28$, $p = .23$.

Discussion

It is clear that the footwear worn during the experiment did not have any effect on female performance: Women wearing casual shoes or flat, paper slippers performed almost identically and, in both conditions, significantly below men. Therefore, we can dismiss the possibility that the female disadvantage in Experiments 1 and 2 is due to an adverse effect of female footwear.

Another possibility is that women might have a poorer ability reorienting by slope because they have more difficulty perceiving or attending to it, independently of the footwear worn. This hypothesis was taken into consideration in Experiment 4.

Experiment 4

To reorient and to memorize the goal's location relative to the slope, one must first be aware of the presence of the slope and must

be able to extract a direction of reference from it. In Experiment 4, we tested whether participants were explicitly aware of the floor's tilt and whether they were able to identify the uphill direction of the slope. Among all possible directions extractable from the slope gradient, the ability to identify the vertical axis was chosen because it is very intuitive (the direction of steepest descent or ascent), it is perceptually meaningful (going uphill requires most effort), and because it is cognitively salient—studies on spatial language have shown a primary role of the up-down axis of spatial reference frames (Carlson & Van Deman, 2008; Franklin & Tversky, 1990).

According to a bottom-up interpretation, sex differences in navigation and spatial abilities result from sex differences at lower, perceptual, or attentional levels of cognitive processing. On the other hand, a top-down interpretation would view sex differences as deriving not from perception or attention but from higher level, cognitive factors (e.g., previous experiences). Experiment 4 examined whether sex differences in the propensity (Experiment 1) and the ability (Experiment 2) to use slope cues are corroborated by sex differences at the perceptual or attentional level of information processing—when there is no goal to find and no strategy to choose.

Method

Twenty male and 20 female Temple University undergraduate students, between 18 and 30 years of age, participated in the experiment. The sample was 52.5% Caucasian, 25% African American, 7.5% Asian, 5% Hispanic, 7.5% of other minorities, and 2.5% undeclared. The average age of men was 19.8 ± 1.45 ; the average age of women was 20.7 ± 2.64 .

The apparatus was identical to previous experiments. Before starting, a participant was told that he/she would be led in an experimental environment and would be asked questions about it. Just as in previous experiments, they had to wear earphones with noise-covering music (at a low volume). Participants were given disposable paper slippers (same as Experiment 3; ScripHessco, Inc.) to wear, instead of their shoes, during the whole experiment. Experiment 3 showed that female performance in reorientation by slope cues is not affected by the footwear. However, because the purpose of Experiment 4 was to test possible sex differences in perception and attention, wearing paper slippers was a conservative measure to ensure that both sexes' sensitivity to the floor was the same.

Experiment 4 was composed of three trials. At the beginning of each trial, a participant was blindfolded and led into the enclosure by the experimenter. The participant sat on the swivel chair and was spun for 1 min, varying speed and direction of rotation. In each trial, the participant started facing a different side of the enclosure (in counterbalanced order across each sex), and the experimenter always stood at the back of the chair. The participant took off the blindfold, stood up, and turned around to face the experimenter. At this point, a question was asked by the experimenter. At the end of each trial, the participant left the enclosure (without a blindfold) and waited outside the room. The approximate time between trials was 2 min.

Trial 1. The enclosure was placed horizontally on the ground. The participant was asked "is the floor slanted?" Participants were not timed.

Trial 2. Same as Trial 1, but now the enclosure was tilted at a 5° angle (the same inclination used in previous experiments). Trials 1 and 2 were given in counterbalanced order across each sex.

Trial 3. Before the participant entered, the experimenter moved the walls (sheets) in the enclosure and readjusted the cloth under the chair. The enclosure was tilted at an inclination of 5° . The participant was told to answer as quickly and as accurately as possible. The request was "point to the uphill side of the enclosure." The participant's response and reaction time (with a wrist stop-watch) were recorded. Timing started right when the request to point ended.

At the end of the experiment, participants took the Water-Level test and were debriefed about the purpose of the experiment. All participants were tested by a male experimenter.

Results

Sex differences with the slope. When the floor was flat and participants were asked whether the floor was slanted (Trial 1), 19 men and 18 women answered correctly. For both sexes, correct responses were above chance (i.e., 50% chance of answering correctly; binomial test: men, $p < .001$; women, $p < .001$). The frequency of correct responses was not significantly different between sexes (Fisher's exact test, $p = 1$).

When the floor was slanted by 5° —the inclination used in previous experiments—(Trial 2) the totality of men and women answered that, indeed, the floor was slanted. It is important to emphasize that the order of presentation of Trials 1 and 2 was counterbalanced across sexes.

When the floor was slanted by 5° and participants were asked to point as quickly and as accurately as possible to the uphill side of the enclosure (Trial 3), 17 men and 17 women pointed correctly. This frequency of correct pointing is above chance (25% correct), $\chi^2(1, N = 20) = 38.40, p < .001$. However, men's reaction time ($1.2 \text{ s} \pm 0.37$) in pointing was shorter than women's reaction time ($2.3 \text{ s} \pm 1.95$): t test for unequal variances, $t(38) = 2.59, p < .05, d = 0.82$.

Further analyses. Performance in the Water-Level test was not significantly different between sexes, $t(38) = 1.38, p = .18$. We examined whether there was a correlation between scores in the Water-Level test and reaction time in pointing uphill; however, the zero-order correlation was not significant, $r(38) = .03, p = .87$, and there was not a significant correlation when controlling for sex, $r(37) = .12, p = .46$.

Discussion

Two main conclusions are justified by this experiment. First, it is clear that perceiving the 5° slope is not a difficult task. Both men and women were able to tell whether the floor was slanted, and their accuracy in pointing to the uphill side of the enclosure was very high—only six participants out of 40 (15%) pointed incorrectly. Participants also did not need a long time to identify the uphill—92.5% of all participants pointed within 3 s, and 85% responded within 2 s. No participant ever walked around, touched the floor with the hands, or needed to perform any movement to sense the slope—standing still was sufficient to respond.

Second, however, against this backdrop of a reasonably easy task, women needed a longer time to point uphill at the same level

of accuracy of men. On average, men pointed 1.1 s more quickly than women (0.82 *SDs*). The sex difference is also apparent when looking at the frequencies of reaction times. Every man responded within 2 s, whereas 30% of women responded in 3 s or more (female reaction time ranged from 1 s to 9 s). Crucially, because there was no accuracy/reaction time tradeoff, the longer time required by women to point to the uphill side of the enclosure suggests that women had a greater difficulty extracting the vertical axis of the slope gradient compared with men. This difficulty could be perceptual, as women might need more time to process and interpret kinesthetic, vestibular, and visual stimuli associated with the slope at a level of confidence. On the other hand, women might perceive the slope as well as men, as indicated by the equivalent accuracies, but might be paying less attention to it, thus requiring more time to attend to slope cues before pointing. Regardless of whether it is a perceptual or an attentional difficulty, the longer reaction time required for identifying the uphill direction substantiates a female difficulty dealing with slope cues independent of complex decisions, as there was no goal to remember and no strategy to choose.

Other explanations remain possible for the sex difference in reaction time; for example, it cannot be excluded that women were simply less confident in judging the uphill (i.e., in a signal detection theory framework, they may have a different criterion rather than a different sensitivity). Psychophysical studies will have to specifically examine the perception of tilted, navigable surfaces and determine more precisely the cause of women's longer reaction time.

General Discussion

The ability to use a navigable, tilted surface to reorient or navigate is extremely relevant to the behavioral ecology of human and nonhuman animals, as slopes are part of the lay of the land in natural environments; however, the literature on this topic is extremely scarce. With respect to humans, there is evidence that the presence of a slope improves navigation in a virtual environment (Restat et al., 2004) and that a terrain slope—together with other cues—can provide directional information for locating a goal in a virtual environment (Chai & Jacobs, 2009). Both of these previous studies provided slope information in conjunction with other sources of spatial information and, importantly, used a virtual-reality environment. The present study represents the first demonstration that slope is sufficient for reorientation; furthermore, this is the first human study on slope to employ a real environment. When it comes to slope, the difference between a real and virtual environment is crucial, as this spatial cue provides multimodal stimuli, of which only the visual subset can be presented via computer monitors.

The weight that participants assigned to each slope-associated, sensory modality was not specifically examined here. Future studies will have to address this issue, dissociating visual from kinesthetic cues and pitting them in conflict to assess how they are integrated into a single, slope representation. For example, participants could be tested in a similar searching task with a blindfold on; this would reveal whether kinesthetic cues are sufficient for reorientation or whether the contribution of vision is necessary. Furthermore, an immersive, virtual-reality setup might be used to place kinesthetic and visual cues in conflict and to determine

which one is dominant for the reorientation process. However, the present study offers some indications on this matter if we consider participants' self-reports on the information used to solve the task. Of the 72 participants that, throughout Experiments 1–3, reported using slope, only three participants (4.2%; two men and one woman) mentioned relying on how the corners looked or on the angle of incidence between sheets and floor (the visual information associated to the slope); all the rest just mentioned that the floor “felt” slanted or that they had to put a different weight on their feet. This hints at a primacy of kinesthetic and vestibular cues over vision for perceiving the slope—at least in our experimental environment—and confirms that reorientation by slope cues in a real environment might be a very different experience compared with a virtual environment stripped of kinesthetic and vestibular information.

A Bi-Coordinate, Slope Representation

How did participants use the slope gradient to find the goal? Important insights can be gained by considering the pattern of incorrect choices during the slope task in Experiments 1–3. Figure 2 shows the experimental environment where the three incorrect corners have been labeled according to a position of the goal in the corner uphill on the left. The raw numbers of errors committed to each corner are reported in the table in Figure 2. Errors were analyzed through comparisons between pairs of incorrect corners (e.g., orthogonal errors vs. vertical errors) using Wilcoxon signed-rank tests with Bonferroni's adjustment for multiple comparisons. The results of these contrasts are also reported in this table.

A simple and straightforward way of using the slope gradient to remember the hiding place is to encode the goal bearing from the center of the enclosure. Following the example in Figure 2, let us consider bearings relative to the slope as if they were cardinal directions, such that the uphill direction is north (N), the downhill direction is south (S), right is east (E), and left is west (W). From the center of the enclosure, each hiding location had a different bearing: NE, SE, SW, and NW. Therefore, participants could just associate the goal location to a goal bearing extracted from the slope (NW in this case). If participants used this strategy, then search errors should be distributed approximately equally between the two corners adjacent to the goal corner (SW and NE) because they have an equal angular distance from the correct bearing (NW); conversely, the diagonally opposite corner (SE) should be less visited because it is farthest away from the correct bearing. However, from the table in Figure 2, it is clear that this was not the pattern of errors actually observed. One corner—orthogonal error (NE)—adjacent to the goal corner, with a correct vertical coordinate (uphill-downhill) but an incorrect orthogonal coordinate (left-right), was visited more frequently than the other two incorrect corners. Considering the data aggregated across experiments, orthogonal errors were committed significantly more than vertical ($p < .001$) and diagonal ($p < .01$) errors; conversely, the frequency of vertical and diagonal errors is approximately the same ($p = 1$). This trend is present even when errors are broken down by experiment and by sex. The fact that, even with a small number of errors, there is a constant prevalence of orthogonal errors—albeit not always statistically significant—suggests that this is a consistent bias in the slope task and for both sexes. Because of this

bias, the pattern of errors in the table in Figure 2 does not support a search strategy based on encoding the goal by its distinctive bearing from the center of the enclosure.

The more frequent searches at the incorrect corner with the correct elevation indicate that the goal was encoded primarily on the basis of its position along the vertical axis of the slope—in other words, on the basis of whether it was uphill or downhill. If, say, the primary axis instead was the orthogonal one, participants should have committed mostly vertical errors—choosing a corner with a correct left-right coordinate but with an incorrect elevation. This suggests that, among all the bearings that can be extracted from the slope gradient, the main axis of reference for reorientation and encoding the goal location is the vertical. However, encoding the goal only as uphill or downhill was insufficient, as there were two hiding places for each vertical coordinate. Therefore, to discriminate the correct corner from the other corner with the same elevation, participants had to include in the representation a distinction based on the orthogonal (left-right) coordinate of the slope. The result is a bi-coordinate representation built on the vertical and orthogonal axes of the slope, such that the goal is encoded, for example, as “the uphill corner on the left.”

The prominence of the vertical and orthogonal axes—compared with all other axes in between—is linked to their cognitive and perceptual meaningfulness: The vertical axis identifies the direction of steepest descent or ascent in the slope gradient, moving along which most energy is required; the orthogonal axis identifies points of the gradient that have equal elevation, moving along which the least amount of energy is required (Restat et al., 2004). The vertical axis of the slope is more salient than the orthogonal because it is linked to a greater energy demand and because it is spatially more informative, as its endpoints (uphill/downhill) are asymmetrical; the endpoints of the orthogonal axis (left/right) instead are symmetrical—no ascent or descent in either direction (Carlson & Van Deman, 2008). The primacy of the vertical axis of the slope over the orthogonal one is consistent with, and extends the findings of, studies of spatial language, which have found a higher priority accorded to the vertical axis relative to the left-right axis of a reference frame (Carlson & Van Deman, 2008; Franklin & Tversky, 1990). Such a hierarchy has been demonstrated also in nonhuman animal place-learning: In a three-dimensional maze, rats show a greater salience of the vertical coordinate of the goal, compared with its horizontal coordinates (Grobéty & Schenk, 1992).

A similar bi-coordinate, slope representation has already been shown in birds. Pigeons had to find a goal among four feeders arranged in a trapezoid or a square array on a slope. Instead of encoding the correct feeder by its specific bearing from the center of the arena, the pattern of searches revealed that the goal was encoded primarily on the basis of its vertical coordinate, with the inclusion of its orthogonal coordinate (Nardi & Bingman, 2009a). It is worth noting that, in a bi-coordinate, slope representation, the vertical coordinate of the goal is necessarily encoded allocentrically—the orthogonal coordinate instead may be included in the representation allocentrically (the goal is uphill and W) or egocentrically (the goal is uphill and, facing uphill, on *my* left). Future studies will have to test whether slope is a mixed representation (allocentric vertical plus egocentric orthogonal axis) or an entirely allocentric representation.

Sex Difference in the Use of a Multi-Modal, Directional Cue

The present sex difference in reorientation by slope can be added to the list of sex differences in spatial cognition shown in mental rotation and spatial perception tasks (Linn & Petersen, 1985; Voyer et al., 1995), in reorientation by geometric cues (Kelly & Bischof, 2005), in navigation abilities in real (Ishikawa & Montello, 2006; Lawton et al., 1996; Saucier et al., 2002; Schinazi et al., 2009) and virtual (Astur et al., 1998; Lawton & Morrin, 1999; Moffat et al., 1998; Sandstrom et al., 1998) environments, in self-reports (Dabbs et al., 1998; Lawton, 1994), and in giving directions (Devlin, 2003; Ward et al., 1986). For most of these differences, there is an advantage in favor of men. However, the majority of the studies on spatial abilities have dealt with visual cues, and there is evidence in support of a lack of sex differences in nonvisual tasks (Alvis et al., 1989; Berthiaume et al., 1993; Biersner, 1980; Livesey & Intili, 1996; Marmor & Zaback, 1976; Passini et al., 1990; Proffitt et al., 1995; Walker, 1972). This suggests that men might be better in visuo-spatial tasks, whereas women might be better in nonvisual tasks (e.g., using auditory or haptic cues; Naylor & McBeath, 2008). In this sense, the present study makes a significant contribution to the literature on dimorphic spatial cognition because it shows a robust male advantage in the use of a multimodal, spatial cue that is not primarily visual but crucially involves kinesthetic and vestibular stimuli.

Which are the factors that contribute to the large sex difference in the use of slope? We have focused on some of the most basic and urgent questions: Does the sex difference lie on men’s greater preference or greater ability for using this strategy (Experiments 1 and 2)? Are women disadvantaged because their perception of the slope is impaired by their footwear (Experiment 3)? Finally, do women have a perceptual or attentional difficulty dealing with slope even without having a goal to find (Experiment 4)? Three factors at three different cognitive levels were identified.

Experiment 1 showed that women are less likely to rely on slope for locating a hidden goal. In fact, more women than men were attempting to use other cues of the environment (e.g., details on the sheets or path integration), although they were ineffective. This supports the claim that sex differences in spatial task performance are driven by dimorphic strategies (Galea & Kimura, 1993; Lawton, 1994; Saucier et al., 2002; Ward et al., 1986).

Experiment 2 showed that, when participants are encouraged to use slope for solving the task, both sexes improve relative to an open task (Experiment 1). However, the sex gap is not closed even when trying to follow the same strategy. Therefore, the female disadvantage cannot be attributed only to a preference for different strategies—it is also due to inferior skills in the use of slope. Distinguishing between dimorphic strategies and dimorphic abilities is important, as the two are often confounded in studies of sex differences in spatial cognition (Saucier et al., 2002).

Experiment 4 revealed that, to be as accurate as men in identifying the uphill side of the enclosure, women required more time. This suggests that women might have a difficulty with perceiving the slope or attending to it. This result is meaningful, as extracting a direction of reference from the slope (e.g., the uphill direction) is a necessary prerequisite for being able to encode the goal location relative to slope.

Therefore, women's disadvantage in the use of slope is present at the perceptual/attentional level (Experiment 4), at the ability level (Experiment 2), and at the strategy-preference level (Experiment 1). The presence of a sex differences at an earlier stage of information processing (perception and attention), when there is no goal to find and no strategy to choose, provides a likely explanation for the differences at later stages, when memory and decision making are involved. Therefore, our data suggest a bottom-up interpretation of the female disadvantage: The perceptual/attentional difficulty in identifying the vertical axis of the slope gradient can account for the inferior ability in reorienting and locating the goal with respect to the slope itself. This, in turn, could be the reason why women rely less on slope cues when required to remember the goal location, preferring to solve the task using other (ineffective) strategies.

Future studies will be necessary to investigate more deeply the causes of this sex difference. We suggest four factors that might be involved. First, women's disadvantage with slope could be due to a general difficulty using directional cues, as proposed by Jacobs and Schenk (2003). Studies using a photograph recognition task (Barkley & Gabriel, 2007) and a goal location task in a virtual environment (Chai & Jacobs, 2009) have shown that, compared with men, women are less sensitive to directional information (e.g., distant landmarks, terrain slopes). The present study extends these findings to a real-world task and supports the hypothesis that men outperform women in navigation and way-finding because of a greater ability in building the directional component of the map-like representation of the environment (*parallel map theory*; Jacobs & Schenk, 2003).

Second, women's disadvantage with slope could be due to a general difficulty engaging the vertical/horizontal reference frame. To solve the slope task, participants had to focus on all the cues (visual, vestibular, and kinesthetic) deriving from the inclination of the enclosure relative to the horizontal plane (determined by the gravity axis). Other tasks that share a similar emphasis on the vertical/horizontal reference frame have also shown a sex difference in favor of men—for example, the estimation of body tilt (Naylor & McBeath, 2008), the verbal judgment of hill slants (Proffitt et al., 1995), the Water Level test, and the Rod and Frame test (Linn & Petersen, 1985; Voyer et al., 1995). It has been suggested that a sex difference might arise because women experience a difficulty in the processing of vestibular information (Sholl, 1989).

Third, it is possible that the physical build of the participants—and height in particular—underlies women's disadvantage with slope. The higher the center of gravity of a person, the more likely a small inclination of the floor will require postural adjustments for balance, increasing the awareness of slope. Therefore, men might have outperformed women in the tasks because they are generally taller. Future research will have to take into account physical parameters of participants and examine whether they correlate with performance independently of sex.

Finally, a fourth possibility—related to that tested in Experiment 3—is that women are disadvantaged in the use of slope because of their experience with footwear. Experiment 3 showed that footwear worn at the time of the experiment did not alter the perception of the slope. However, women's ability to use slope might be impaired by a history of wearing heels—possibly of varying heights—that rendered perceived foot tilt irrelevant. Future re-

search will have to address this issue and investigate whether there is a correlation between task performance and footwear habits.

Conclusions

This study shows that human adults are able to regain a sense of orientation and to find a goal using only cues associated with terrain slope. The experimental environment provided all the cues available in natural conditions when navigating on a sloped terrain: kinesthetic cues from joint angles and muscular effort, vestibular cues, and visual cues from the angles between vertical objects (the walls) and the tilted floor (the angle of incidence between the walls and the floor was slightly obtuse on the uphill side of the enclosure and was slightly acute on the downhill side; see Figure 1B). If participants were able to reorient by slope cues in our controlled environment, then surely they should be able to use slope in a natural environment with many vertical objects (buildings and trees) that enrich the visual cues associated with the slope.

In a square environment with four hiding places, we propose that a bi-coordinate representation is used: The goal is encoded primarily on the basis of its location relative to the vertical axis and is encoded secondarily relative to the orthogonal axis of the slope. To further our understanding of the role of topography in spatial learning, future studies should address how slope is represented in larger and more complex environments, and how it is used in combination with other spatial information (e.g., landmarks) for large-scale navigation.

References

- Alvis, G. R., Ward, J. R., & Dodson, D. L. (1989). Equivalence of male and female performance on a tactual-spatial maze. *Bulletin of the Psychonomic Society*, *27*, 29–30.
- Astur, R. S., Ortiz, M. L., & Sutherland, R. J. (1998). A characterization of performance by men and women in a virtual Morris water task: A large and reliable sex difference. *Behavioural Brain Research*, *93*, 185–190. doi:10.1016/S0166-4328(98)00019-9
- Barkley, C. L., & Gabriel, K. I. (2007). Sex differences in cue perception in a visual scene: Investigation of cue type. *Behavioral Neuroscience*, *121*, 291–300. doi:10.1037/0735-7044.121.2.291
- Berthiaume, F., Robert, M., St-Onge, R., & Pelletier, J. (1993). Absence of a gender difference in a haptic version of the water-level task. *Bulletin of the Psychonomic Society*, *31*, 57–60.
- Biersner, R. J. (1980). Sex differences in right- and left-hand tactualmotor acquisition practice. *Perceptual and Motor Skills*, *50*, 986.
- Carlson, L. A., & Van Deman, S. R. (2008). Inhibition within a reference frame during the interpretation of spatial language. *Cognition*, *106*, 384–407. doi:10.1016/j.cognition.2007.03.009
- Chai, X. J., & Jacobs, L. F. (2009). Sex difference in directional cue use in a virtual landscape. *Behavioral Neuroscience*, *123*, 276–283. doi:10.1037/a0014722
- Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, *23*, 149–178. doi:10.1016/0010-0277(86)90041-7
- Cheng, K. (2008). Whither geometry? Troubles of the geometric module. *Trends in Cognitive Sciences*, *12*, 355–361. doi:10.1016/j.tics.2008.06.004
- Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic Bulletin & Review*, *12*, 1–23.
- Dabbs, J. M., Jr., Chang, E. L., Strong, R. A., & Milun, R. (1998). Spatial ability, navigation strategy, and geographic knowledge among men and women. *Evolution and Human Behavior*, *19*, 89–98. doi:10.1016/S1090-5138(97)00107-4

- Devlin, A. S. (2003). Giving directions: Gender and perceived quality. *Journal of Applied Social Psychology, 33*, 1530–1551. doi:10.1111/j.1559-1816.2003.tb01961.x
- Durgin, F. H., Hajnal, A., Li, Z., Tonge, N., & Stigliani, A. (2010). Palm boards are not action measures: An alternative to the two-systems theory of geographical slant perception. *Acta Psychologica, 134*, 182–197.
- Franklin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General, 119*, 63–76. doi:10.1037/0096-3445.119.1.63
- Galea, L. A., & Kimura, D. (1993). Sex differences in route-learning. *Personality and Individual Differences, 14*, 53–65. doi:10.1016/0191-8869(93)90174-2
- Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.
- Grobóty, M. C., & Schenk, F. (1992). Spatial learning in a three-dimensional maze. *Animal Behaviour, 43*, 1011–1020. doi:10.1016/S0003-3472(06)80014-X
- Hampton, R. R., & Shettleworth, S. J. (1996). Hippocampal lesions impair memory for location but not color in passerine birds. *Behavioral Neuroscience, 110*, 831–835. doi:10.1037/0735-7044.110.4.831
- Hermer, L., & Spelke, E. (1994, July 7). A geometric process for spatial representation in young children. *Nature, 370*, 57–59. doi:10.1038/370057a0
- Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition, 61*, 195–232. doi:10.1016/S0010-0277(96)00714-7
- Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive Psychology, 52*, 93–129. doi:10.1016/j.cogpsych.2005.08.003
- Jacobs, L. F., & Schenk, F. (2003). Unpacking the cognitive map: The parallel map theory of hippocampal function. *Psychological Review, 110*, 285–315. doi:10.1037/0033-295X.110.2.285
- Kelly, D. M., & Bischof, W. F. (2005). Reorienting in images of a three-dimensional environment. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 1391–1403. doi:10.1037/0096-1523.31.6.1391
- Lawton, C. A. (1994). Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety. *Sex Roles, 30*, 765–779. doi:10.1007/BF01544230
- Lawton, C. A., Charleston, S. I., & Zieles, A. S. (1996). Individual- and gender-related differences in indoor wayfinding. *Environment and Behavior, 28*, 204–219. doi:10.1177/0013916596282003
- Lawton, C. A., & Morrin, K. A. (1999). Gender differences in pointing accuracy in computer-simulated 3D mazes. *Sex roles, 40*, 73–92. doi:10.1023/A:1018830401088
- Liben, L. S. (1995). Educational applications of geographic information systems: A developmental psychologist's perspective. In D. Barstow (Ed.), *First national conference on the educational applications of geographic information systems* (pp. 44–49). Cambridge, MA: TERC.
- Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*, 1479–1498. doi:10.2307/1130467
- Livesey, D. J., & Intili, D. (1996). A gender difference in visuo-spatial ability in 4-year-old children: Effects on performance of a kinesthetic acuity task. *Journal of Experimental Child Psychology, 63*, 436–446. doi:10.1006/jecp.1996.0057
- Marmor, G. S., & Zaback, L. A. (1976). Mental rotation by the blind: Does mental rotation depend on visual imagery? *Journal of Experimental Psychology: Human Perception and Performance, 2*, 515–521. doi:10.1037/0096-1523.2.4.515
- McGregor, A., Hayward, A. J., Pearce, J. M., & Good, M. A. (2004). Hippocampal lesions disrupt navigation based on the shape of the environment. *Behavioral Neuroscience, 118*, 1011–1021. doi:10.1037/0735-7044.118.5.1011
- Miniaci, M. C., Scotto, P., & Bures, J. (1999). Place navigation in rats guided by a vestibular and kinesthetic orienting gradient. *Behavioural Neuroscience, 113*, 1115–1126. doi:10.1037/0735-7044.113.6.1115
- Moffat, S. D., Hampson, E., & Hatzipantelis, M. (1998). Navigation in a “virtual” maze: Sex differences and correlation with psychometric measures of spatial ability in humans. *Evolution and Human Behavior, 19*, 73–87. doi:10.1016/S1090-5138(97)00104-9
- Nardi, D., & Bingman, V. P. (2009a). Pigeon (*Columba livia*) encoding of a goal location: The relative importance of shape geometry and slope information. *Journal of Comparative Psychology, 123*, 204–216. doi:10.1037/a0015093
- Nardi, D., & Bingman, V. P. (2009b). Slope-based encoding of a goal location is unaffected by hippocampal lesions in homing pigeons (*Columba livia*). *Behavioral Brain Research, 205*, 322–326. doi:10.1016/j.bbr.2009.08.018
- Nardi, D., Nitsch, K. P., & Bingman, V. P. (2010). Slope-driven goal location behavior in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*. Advance online publication. doi:10.1037/a0019234
- Nashner, L. M. (1983). Analysis of movement control in man using the movable platform. *Advances in Neurology, 39*, 607–619.
- Naylor, Y. K., & McBeath, M. K. (2008). Gender differences in spatial perception of body tilt. *Perception & Psychophysics, 70*, 199–207. doi:10.3758/PP.70.2.199
- Passini, R., Proulx, G., & Rainville, C. (1990). The spatio-cognitive abilities of the visually impaired population. *Environment and Behavior, 22*, 91–118. doi:10.1177/0013916590221005
- Piaget, J., & Inhelder, B. (1956). *The child's conception of space*. London, England: Routledge & Kegan-Paul.
- Proffitt, D. R., Bhalla, M., Gossweiler, M., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic Bulletin & Review, 2*, 409–428.
- Restat, J. D., Steck, S. D., Mochnatzki, H. F., & Mallot, H. A. (2004). Geographical slant facilitates navigation and orientation in virtual environments. *Perception, 33*, 667–687. doi:10.1068/p5030
- Sandstrom, N. J., Kaufman, J., & Huettel, S. A. (1998). Males and females use different distal cues in a virtual environment navigation task. *Cognitive Brain Research, 6*, 351–360. doi:10.1016/S0926-6410(98)00002-0
- Saucier, D. M., Green, S. M., Leason, J., MacFadden, A., Bell, S., & Elias, L. J. (2002). Are sex differences in navigation caused by sexually dimorphic strategies or by sex differences in the ability to use strategies? *Behavioral Neuroscience, 116*, 403–410. doi:10.1037/0735-7044.116.3.403
- Schinazi, V. R., Epstein, R. A., Nardi, D., Newcombe, N. S., & Shipley, T. F. (2009, November). *The acquisition of spatial knowledge in an unfamiliar campus environment*. Poster presented at the annual meeting of the Psychonomic Society, Boston, MA.
- Sholl, M. J. (1989). The relation between horizontality and rod-and-frame and vestibular navigation performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 110–125. doi:10.1037/0278-7393.15.1.110
- Strasser, R., & Bingman, V. P. (1997). Goal recognition and hippocampal formation in the homing pigeon (*Columba livia*). *Behavioral Neuroscience, 111*, 1245–1256. doi:10.1037/0735-7044.111.6.1245
- Sutton, J. E., Joannisse, M. F., & Newcombe, N. S. (2010). Spinning in the scanner: Neural correlates of virtual reorientation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 1097–1107.
- Twyman, A. D., & Newcombe, N. S. (2010). Five reasons to doubt the existence of a geometric module. *Cognitive Science, 34*, 1315–1356. doi:10.1111/j.1551-6709.2009.01081.x
- Vargas, J. P., Petruso, E. J., & Bingman, V. P. (2004). Hippocampal formation is required for geometric navigation in pigeons. *European*

- Journal of Neuroscience*, 20, 1937–1944. doi:10.1111/j.1460-9568.2004.03654.x
- Von Frisch, K. (1967). *The dance language and orientation of bees*. Cambridge, MA: Harvard University Press.
- Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, 117, 250–270. doi:10.1037/0033-2909.117.2.250
- Walker, J. T. (1972). Tactual field dependence. *Psychonomic Science*, 26, 311–313.
- Wang, R. F., & Spelke, E. S. (2002). Human spatial representation: Insights from animals. *Trends in Cognitive Sciences*, 6, 376–382. doi:10.1016/S1364-6613(02)01961-7
- Ward, S. L., Newcombe, N., & Overton, W. F. (1986). Turn left at the church, or three miles north: A study of direction giving and sex differences. *Environment and Behavior*, 18, 192–213. doi:10.1177/0013916586182003

Received December 15, 2009

Revision received August 9, 2010

Accepted August 28, 2010 ■