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The Role of Slope in Human Reorientation

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Abstract. Studies of spatial representation generally focus on flat environments and visual stimuli. However, the world is not flat, and slopes are part of many natural environments. In a series of four 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. Participants succeeded in the task; however, a large sex difference emerged. Men showed a greater ability in using slope and a greater preference for relying on slope as a searching strategy. The female disadvantage was not due to wearing heeled shoes, but was probably related to a greater difficulty in extracting the vertical axis of the slope.

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

1 Introduction

Re-gaining a sense of orientation once we have lost track of where we are – a process called reorientation – is an essential ability for any mobile animal. It is based on the recognition of one or more key elements of the environment (e.g., a celestial cue, a distinctive building, a sound) that provide a sense of "where we are". In the past 25 years, because of the claim that reorientation is selectively attuned to the geometric shape of the environment (the "geometric module" hypothesis; [1]), most research attention has been focused on visual cues; specifically, on whether human and nonhuman animals can reorient using a geometric layout of walls, and can integrate this information with other visual feature cues (e.g., landmarks).

One spatial cue that has been neglected is the three-dimensional topography of the land. Most of the research on spatial cognition is carried out on completely horizontal surfaces; however, the world is not flat, and we live and move on surfaces of varying elevation – both in man-made and in natural settings. Therefore, it is crucial to examine how space is represented in vertically extended environment, such as dunes, hills and mountains. Vertical topography is a distinctively salient spatial cue for three main reasons. First, this terrain feature is very stable in time and space, whereas other visual features of the environment may change rapidly in the course of a day (different lighting between day and night) or of a season (leafs fall from trees, snow covers vegetation, rivers dry out in summer); because of this permanent nature, vertical topography is a reliable source of spatial information. Second, navigable surfaces ex-tended in the vertical dimension are salient because movements with a vertical component are generally more effortful compared to movements on a horizontal, flat plane; the energy demand associated with counteracting the force of gravity renders the vertical dimension of space cognitively salient. Third, movements with a vertical component provide a suite of multimodal sensory activations, which differ from locomotion on a horizontal surface, as a consequence of kinesthetic, proprioceptive, vestibular and visual stimuli; this multimodal redundancy renders vertical topography uniquely salient.

The simplest surface extended in the vertical dimension is a slope (also called geo-graphical slant; [2]). This 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 compass-like bearings extracted from the slope gradient, the two major ones being the vertical axis (uphill/downhill: the direction of steepest descent) and the orthogonal axis of the slope (left/right: direction of no descent; [3]). A slope can be perceived by the different effort when moving uphill, downhill or sideways (kinesthetic information), by the angles of the joints (proprioceptive information), by the sense of balance (vestibular information), and by visual cues (e.g., the angle of incidence be-tween a tree and a slope is acute on the uphill side and obtuse on the downhill side); we refer to these cues collectively as "slope cues" or "slope information".

Most of the research on slope as a means for reorientation comes from studies on pigeons. It has been shown that pigeons, just like rats [4], can use a slope to locate a goal in an otherwise featureless environment [5]. Lesion studies suggest that this representation is hippocampal-independent [6], similarly to representations based on visual features [7], whereas a geometry-based representation is hippocampal-dependent [8]. When slope and geometry are set in conflict, pigeons preferentially choose the corner that is geometrically incorrect, but that has a correct position relative to the slope [5]. Importantly, slope seems to guide behavior even when it is rendered less informative than geometry [9], suggesting that slope's salience is so high that it can compensate for a lower predictive value. These findings argue against a primacy of geometric information [1]; furthermore, because the preferred corner is visually incorrect, they do not sup-port a view-based matching strategy for solving reorientation tasks [10].

In humans, there is evidence that the presence of a slope improves navigation in a virtual environment [3], and that a terrain slope – together with other cues – can provide directional information for locating a goal in a virtual environment [11]. However, no study to date has examined whether humans can reorient simply by using a tilted surface, and if 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. Therefore, 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 the study here summarized was to investigate the simple – but crucial – question of whether humans are able to reorient by slope.

In spatial cognition, a male advantage is often reported in psychometric tests of mental rotation and spatial perception [12]. Furthermore, a male advantage has been shown in reorientation by geometric cues in a virtual environment [13], and, when way-finding or navigation abilities are measured, sex differences appear in real-world environments [14] and in virtual environments [15]. Therefore, a secondary goal of the study here summarized was to investigate if sex differences apply to the use of this novel spatial cue – slope.

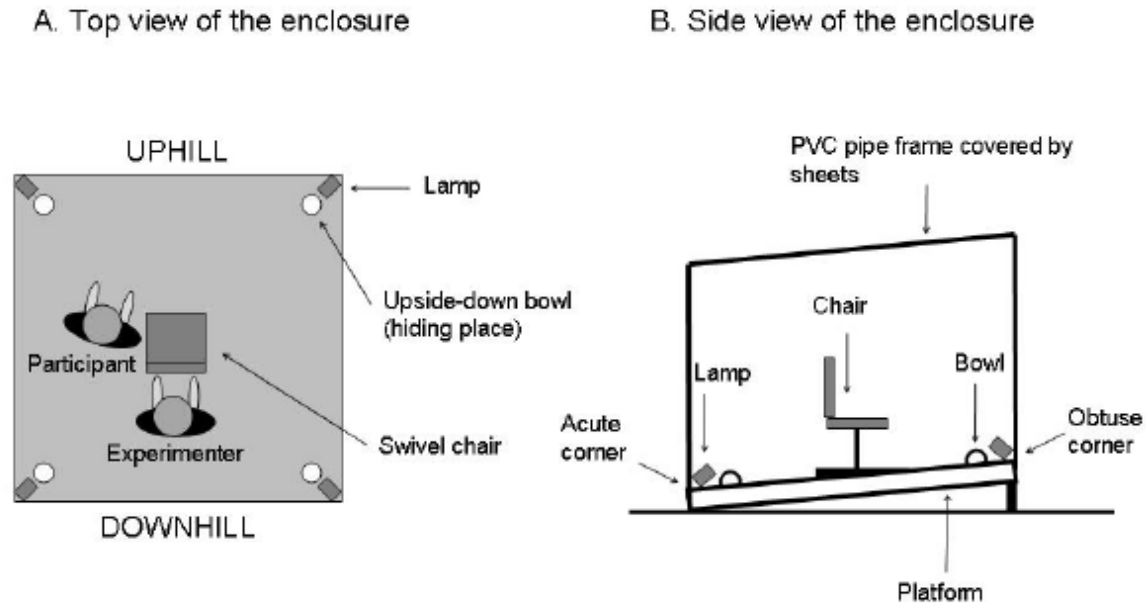

Fig. 1. Schematic representation of the experimental enclosure viewed from above (A) and from the side (B). The size of the enclosure was 244 x 244 cm, and 203 cm high. The enclosure was tilted at an inclination of 5°, but could also be placed horizontally on the ground. In each corner of the enclosure there was a 25-W lamp and a red bowl placed upside-down, which constituted the hiding place for the target (a $1 bill). A swivel chair was placed in the center of the enclosure. 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. It is important to note that, when spinning on the swivel chair, the subjects' feet never touched the floor, so no cues were available for keeping track of their position relative to the slope. Each time, a participant en-tered the enclosure with the blindfold on.

2 Experiment 1

Twenty male and 20 female Temple University undergraduate students participated. Subjects were shown a target being hidden in one of the corners of a square enclosure (for details see Fig. 1); then they were blindfolded and spun on a swivel chair, to make them lose their sense of orientation. After this, they took off the blindfold, stood up and had to walk to the hidden object. The enclosure was completely featureless, and the square shape did not enable a distinction of the corners based on geometry. However, the enclosure was slanted by a 5° angle – an inclination that pilot studies proved to be easily perceived. Therefore, the goal corner could be identified based on its location relative to the slope gradient (e.g., facing uphill, the goal is on the right; see Fig. 1).

For 4 trials (training phase), the target was always in the same corner (a reference memory paradigm) and participants were given feedback. Both men and women located the target above chance, men: $t(19) = 14.33$, $p < .001$; women $t(19) = 2.41$, $p < .05$. However, men performed significantly better than women (79% vs. 43% correct trials, respectively), $t(38) = 4.43$, $p < .001$, with a difference of 1.4 standard deviations (Fig. 2). After training, two test trials without feedback were carried out to en-sure that participants were relying only on slope cues to locate the target. In one trial, the enclosure was placed horizontally on the ground; if participants encoded the goal using slope, now they should be unable to find the target. In a second trial, the enclosure was tilted, just like during training; therefore, participants should be able to use the slope and locate the target. During these test trials (which were in counterbalanced order) both men and women performed at chance when the enclosure was flat (binomial test, males: $p = 1$; females: $p = .80$), and performed above chance when the en-closure was tilted (binomial test, males: $p < .001$; females: $p < .05$), suggesting that, indeed, participants were relying only on slope cues to solve the task.

These results provide the first demonstration that human adults can use terrain slope to reorient and locate a goal in a real-world environment. Using a similar square arrangement of hiding places on a tilted, navigable surface, it has already been shown that rats [4] and pigeons [5] can use the slope to find a goal. Therefore, it was not un-expected that humans could succeed in such a task. However, surprisingly, a large sex difference emerged. Participants could have attempted to use cues other than slope to solve the task (e.g., path integration, details of the enclosure), even though these were ineffective strategies. In this sense, this experiment shows that men have a greater disposition to rely on the only cue that consistently predicted the goal – slope – whereas women might attempt to use more other cues. A different question would be: is there a sex difference in the ability to use slope? Women could be less disposed, but not less able, to use slope for reorientation.

3 Experiment 2

Twenty male and 20 female Temple University undergraduate students participated. The procedure consisted of the same four training trials as in Experiment1 (test trials were not carried out now). However, participants' attention was drawn to the tilt of the floor by showing a ball rolling on the floor of the enclosure. Furthermore, the ex-perimenter suggested that the slope should help in remembering the hiding place. With a clear demonstration that the floor is tilted and an encouragement to rely on it to solve the task, Experiment 2 measured more specifically the ability – rather than the disposition – to use slope information.

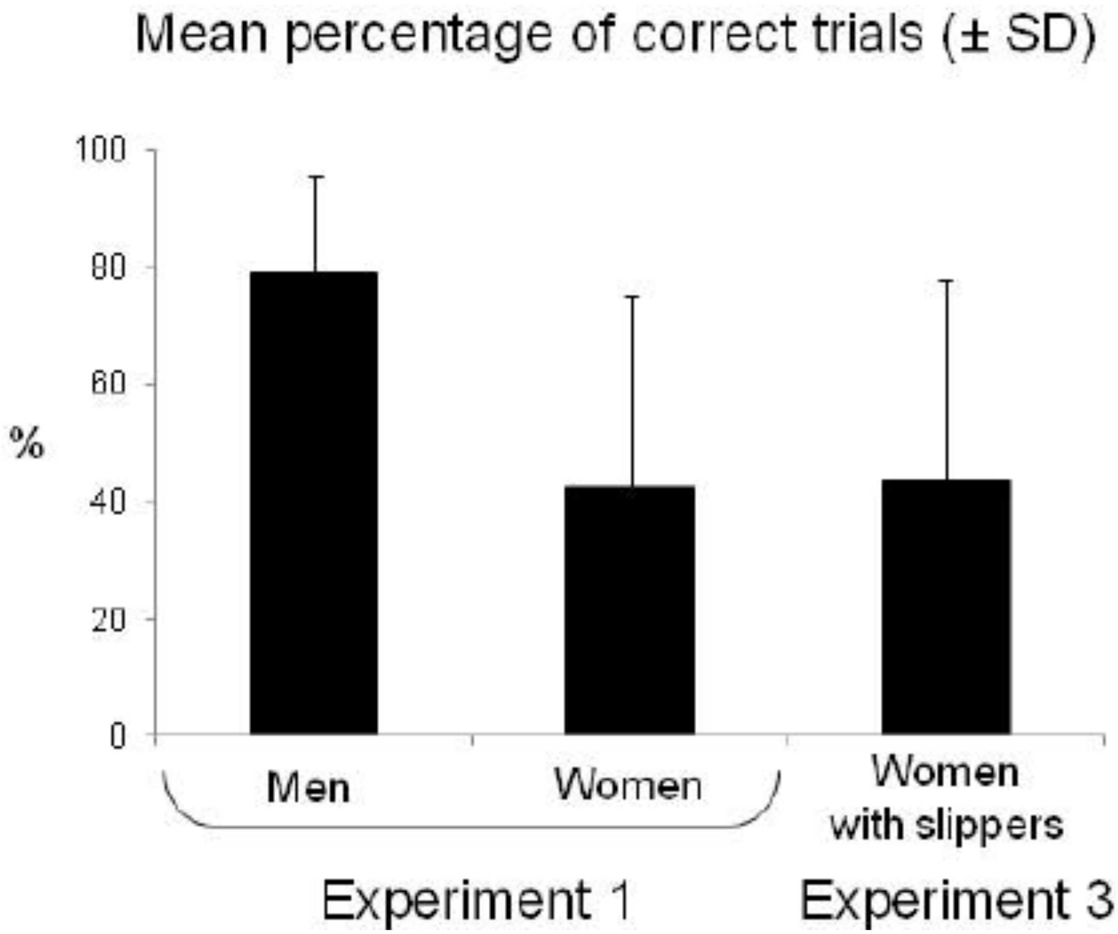

Fig. 2. Mean percentage of correct trials (± SD) during the 4 training trials in Experiment 1 and in Experiment 3. In Experiment 1 men and women wore casual footwear, whereas in Experiment 3 women wore flat, paper slippers. Men performed significantly more correct trials than women with casual footwear or paper slippers. Women wearing casual footwear and paper slippers performed similarly.

The percentage of correct trials increased relative to Experiment 1, $F[1,76] = 15.97$, $MSE = 669.82$, $p < .001$ (Fig. 3). However, men still performed significantly better than women (94% vs. 74% correct trials), $t(38) = 2.44$, $p < .05$, $d = .77$. Com-paring performance between Experiment 1 and 2, there was not a significant sex-by-experiment interaction, $F[1,76] = 1.97$, $p = .16$, $\eta 2p = .03$. Therefore, it seems that a gap between the sexes exists not only in the disposition to rely on slope cues (as shown in Experiment 1), but also in the ability to use them, because men, when prompted to use slope, performed near ceiling, whereas women still had room for improvement.

4 Experiment 3

What are the factors behind this female disadvantage with slope cues? In Experiment 3 we take into consideration a possibility related to cultural, gender-specific use of footwear. Women's casual footwear is much more likely to present heels, even if moderate, compared to men. Walking on such shoes could introduce a bias in the perception of a sloped floor, rendering kinesthetic and vestibular cues less reliable. This, in turn, could reduce women's sensitivity to slope and impair their ability to use slope for reorientation. In Experiment 3, twenty women were tested in an identical task as in Experiment 1; however, this time they wore disposable paper slippers, which are completely flat. Performance during the four trials was compared with Experiment 1, in which participants wore casual shoes, so that it was possible to test if heels are responsible for the sex gap in reorientation by slope. If women were disadvantaged relative to men because of the heels associated with their casual footwear, their performance in Experiment 3 should be higher than in Experiment 1.

Female performance with paper slippers paralleled that of females with casual shoes in Experiment 1, $t(38) = .12$, $p = .91$ (Fig. 2). The mean percentages of correct trials and the variability were almost identical. 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, $t(38) = 4.10$, $p < .001$, $d = 1.30$. Therefore, we can dismiss the possibility that the female disadvantage in Experiment 1 and 2 is due to an adverse effect of female footwear.

5 Experiment 4

In order to use slope for reorientation, one must first be aware of the slope gradient and must be able to extract a direction of reference from it. Experiment 4 examined whether there is a sex difference at these earlier, perceptual stages, as this might be responsible for the female disadvantage using slope for reorientation. Twenty male and 20 female Temple University undergraduate students participated. The same apparatus from previous experiments was used. All participants wore disposable, paper slippers. For three trials participants entered the enclosure and were spun on the swivel chair blindfolded; then they took off the blindfold and were asked a question.

In the first two trials, participants had to judge whether the enclosure was tilted or not. In one trial it was tilted, and in another trial it was placed horizontally on the ground (counterbalanced order). Men and women judged equally well, showing that their awareness of the slope was similar. Then, in the third trial, participants were asked to point as quickly and as accurately as possible to the uphill side of the enclosure. This requires the identification of the vertical axis of the slope, which is considered the most salient direction that can be extracted from the slope, as it is the axis of steepest descent, moving along which most energy is required [5], [16]. Men and women were equally accurate, but men had a significantly shorter reaction time (1.2 vs. 2.3 seconds, respectively), $t(38) = 2.59$, $p < .05$, $d = .82$. Because there was no accuracy/reaction-time trade-off, this suggests that women had more difficulty identifying the uphill direction at the same level of accuracy as men.

Women's difficulty could be perceptual, as they might need more time to process and interpret kinesthetic, vestibular and visual stimuli associated with the slope at a level of confidence. Alternatively, women might perceive the slope as well as men, as suggested 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 attentional difficulty, the longer reaction time in identifying the up-hill direction substantiates a female difficulty in dealing with slope cues independent of complex decisions, as there was no goal to remember and no strategy to choose.

6 Conclusions

The present study represents the first demonstration that slope is sufficient for reorientation in humans. This ability is ecologically relevant, as slopes are part of the lay of the land in natural environments. Furthermore, this is the first human study on slope that employs a real environment. When it comes to slope information, 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.

Although both men and women were able to reorient by slope cues, a large male advantage emerged. This can be added to the list of sex differences in spatial cognition shown in mental rotation and spatial perception tasks [12], in reorientation by geometric cues [13], in navigation abilities in real [14] and virtual environments [15]. For most of these differences, there is an advantage in favor of males. However, there is evidence in support of a lack of sex differences in non-visual tasks [2], [17], [18], [19]. One interpretation of these data would suggest that men might have an advantage with visuo-spatial tasks, rather than with spatial tasks per se. 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 spatial cue that is not primarily visual, but crucially involves kinesthetic and vestibular stimuli.

Women's disadvantage in using slope is present at the level of perception/attention (Experiment 4), at the level of ability (Experiment 2), and at the level of strategy-preference (Experiment 1). The presence of a sex differences at an earlier stage of information processing (perception and attention) provides a likely explanation for the differences at later stages, when memory of the goal and decision making are in-volved. Therefore, our data suggest a bottom-up interpretation of the female disadvan-tage: the 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; this, in turn, could be the reason why females attempt to use other, ineffective strategies to solve the task.

7 Future Directions

Future studies will be necessary to investigate more deeply the causes of this sex difference. First, it would be interesting to consider if previous experience with slope or, more generally, with directional cues might affect the ability to use slope, in a top-down fashion. Previous studies have suggested that women, compared to men, might be less attuned to directional cues [20]; to what extent can training compensate for this disadvantage?

From Fig. 2 and Fig. 3, it is clear that women had a much larger variability in performance compared to men. This individual difference is linked to the large variety of strategies used: women, more so than men, attempted to rely on other cues to solve the task (e.g., path integration), even though they were ineffective. It would be of extreme interest to find out why some women used slope and some others did not, and if this strategy-preference is correlated to any type of spatial ability (e.g., mental rotation or perspective taking).

Furthermore, one hypothesis that should be contemplated is that the physical build of the participants – and height in particular – may underlie 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 aware-ness 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 if they correlate with performance independently of sex.

Finally, it is possible that women are disadvantaged in the use of slope because of their previous 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 of different height that rendered perceived foot tilt irrelevant. Future research will have to address this issue and investigate if there is a correlation between task performance and footwear habits.

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