Cogn Process (2015) 16 (Suppl 1):S323–S326
DOI 10.1007/s10339-015-0669-x

SHORT REPORT

Sex differences and errors in the use of terrain slope for navigation

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Published online: 28 July 2015

Abstract Unlike most of the spatial cues that have received attention, a sloping terrain can be perceived by multimodal sensory inputs (vision, balance, and kinesthesia), making it potentially very salient for navigation. Furthermore, a homogeneous slope can be used like a compass to identify directions (e.g., uphill, downhill, and sideways), but not to determine distances. We briefly review recent evidence on navigation with slope, emphasizing two main findings. On the one hand, we focus on the conspicuous sex difference found in the ability to localize a target in a square, tilted enclosure; this has emerged in human adults and children, and we suggest that it is related to lower awareness of the slope for females. On the other hand, we describe the general pattern of errors that arises when localizing the target during the task; these errors indicate the use of a bi-coordinate representation of the slope. Limitations and ideas for future studies are proposed.

Keywords Navigation · Reorientation · Slope · Sex differences · Spatial representation

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Introduction

To date, the bulk of the literature on navigation and spatial orientation focuses on flat, horizontal planes (for a recent review, see Cheng et al. 2013). However, non-horizontal surfaces, such as mountains or hills, provide an extra spatial cue—terrain slope—that can be used to reorient (identifying facing direction after being disoriented). In a hilly neighborhood, for example, one might remember that the car is parked "uphill and on the left." The target would be encoded using the slope gradient as an allocentric directional reference frame (e.g., uphill could be likened to north and downhill to south).

Terrain slope is a unique spatial cue in that it can be perceived via multiple sensory modalities (visual, vestibular, and kinesthetic cues) and is associated with effortful movements. As such, it has the potential of being a very salient type of information, and in fact, it is used to localize a target even when more predictive spatial cues (layout geometry) are available (Nardi et al. 2010). However, this prioritization has only been demonstrated with steep inclinations (20°) and using non-human animal models (homing pigeons). In human studies, which have used non-comparable experimental procedures (e.g., shallower inclinations), the slope does not seem to dominate over other cues (Kelly 2011; Nardi et al. 2013).

Furthermore, slope derives its theoretical importance from being a gradient that—at least when homogeneous (constant gradient)—provides direction information only (for an extended discussion, see Holmes et al. 2015). Most spatial cues tested in reorientation studies provide directional *and* distance information. For example, positional cues (e.g., landmarks or beacons) are local to the target and can be used to encode a short vector to the target location (Jacobs and Schenk 2003). Directional cues are different—

they are distal to the target, provide only bearing information, and can be used to integrate different local environments into a cohesive global representation (e.g., a distant, static landmark provides a stable direction of reference from multiple perspectives; Jacobs and Schenk 2003). Despite this, directional cues—and gradient cues in particular—have been neglected.[1]

The purpose of this paper is to briefly review the evidence on the ability to use terrain slope for navigation, with an emphasis on two main findings: the sex differences and the error pattern.

Sex differences

The first study carried out on human reorientation with terrain slope used a goal-searching task. In this paradigm, participants encoded a target hidden in one of four corners of a square, featureless environment, polarized only by the slant of the floor (5° steep), and were asked to locate the target following disorientation (Nardi et al. 2011). Despite being an intuitively simple task, there was a remarkable variability in performance: a quarter of the sample performed at ceiling, but just as many performed at chance. One factor that easily captured this variability was sex, with men outperforming women. Sex differences in spatial cognition are not uncommon (Lawton 2010). What was surprising was the magnitude of the effect size (1.4 *SD*), which exceeded that found in mental rotation, a spatial skill with the largest, and most pervasive, effect of sex (Voyer et al. 1995). Overall, the findings of Nardi et al. (2011) indicated that females were less able to use the slope; however, it is not clear whether this was related to being less aware of it.

The male advantage in using slope for reorientation has been supported by further evidence (e.g., Nardi et al. 2014; Weisberg et al. 2014), but one study is particularly informative. Holmes et al. (2015), using the same task as Nardi et al. (2011), tested 8- to 10-year-old children. The purpose of the study was to examine slope performance at an age that precludes hormonal changes related to pubertal onset, as well as the potentially detrimental effects of heeled footwear on sensitivity to underfoot slant. Crucially, before starting the task, participants were asked whether they noticed anything unusual about the enclosure, which measured the extent to which slope was spontaneously detected. It is important to note that a 5° incline (approximately 1:12 ratio), while not steep, is easy to discriminate from a flat surface (to give an idea, it is a standard inclination used for wheelchair ramps; Nardi et al. 2011). The sex difference in performance found in adults was replicated in children. In addition, boys were more likely than girls to notice the slope, and spontaneous slope perception mediated performance in the slope task. In other words, participants who spontaneously noticed that the floor was tilted outperformed those who did not, and once this variable was taken into account, performance no longer differed by sex.

This finding suggests that the female disadvantage is related to attenuated slope awareness, which may be linked to lower cue salience. A perceptual/attentional difficulty with slope is reinforced by the fact that women had lower performance even in a simple task requiring identification of the uphill direction (Nardi et al. 2011, 2014). Another possible interpretation is that women might have a more conservative criterion for judging slope, not lower sensitivity. Relevant to this, it has been found that, when choices and confidence in making said choices were separately measured, women only displayed lower confidence in localizing the target using the slope (Nardi et al. 2013). Inferior spatial confidence for females has also been shown in different contexts (e.g., cognitive mapping task: O'Laughlin and Brubaker 1998), and the way it affects spatial behavior should be explored more in depth.

To the best of our knowledge, the only studies that did not detect a sex difference are those that examined slope in large-scale virtual environments, in which the slope cue is immersed in a rich set of alternate spatial cues (Restat et al. 2004; Weisberg and Newcombe 2014). Therefore, this sex difference seems to be pervasive (see also Chai and Jacobs 2009, 2010), and it deserves further attention because it may help identify ways to eliminate the disadvantage and improve spatial abilities. In particular, it would be important to study the extent to which the sex difference is explained by experiential factors—e.g., decreased exposure and interaction with directional or gradient cues for females.

Error pattern

To date, only a square enclosure with a 5° inclination and only discrete corner locations have been used to systematically examine slope as a necessary and sufficient spatial cue. In this condition, the target corner can be determined by combining a vertical coordinate (uphill or downhill) with an orthogonal coordinate (left or right); alternatively, it can be determined by a "goal bearing" relative to the slope (following the analogy between uphill and north, the target could be encoded as being, for example, in the northeast corner, with respect to the center of the enclosure). Which representation do people use?

[1] It should be noted that Jacobs and Schenk (2003) consider environmental geometry as a directional cue. Conversely, at least in the context of small enclosures with bounding walls, we consider environmental geometry as a positional cue (a wall or corner provides a local cue).

Results consistently show that choices to the correct corner are above chance; however, when incorrect, choices are not evenly distributed (randomly) among the incorrect corners. People tend to make an orthogonal error most frequently, choosing the corner at the correct elevation, but incorrect on the left–right axis. This pattern of errors significantly emerges in adults (Nardi et al. 2011; Weisberg et al. 2014) and in children (Holmes et al. 2015), suggesting that people are using a bi-coordinate representation of the goal (vertical plus orthogonal coordinate), with the vertical coordinate more salient than the orthogonal, such that choices tend to be concentrated at the correct elevation—although sometimes at an incorrect left–right corner.

This type of representation is consistent with the vertical axis' preferential assignment in memory compared to other egocentric axes—especially the left–right axis (Franklin and Tversky 1990). Even non-human animals show a behavior congruent with orthogonal errors: Homing pigeons, for example, trained to find food in different shaped enclosures, tend to cluster their second choices to the corner at the correct elevation (Nardi and Bingman 2009). This behavior indicates that the bi-coordinate representation may be diffused and that it is not related to verbal coding. Interestingly, orthogonal errors did not appear in a study that used a slanted ceiling as a gradient cue (Hu et al. 2015). In one of the conditions, 3- to 4-year-olds were tested in a square room in which polarizing information was provided by the gradually changing ceiling height. The fact that orthogonal errors were not predominant suggests that there might be something unique about a slanted, navigable surface—perhaps the effort and kinesthetic stimulation involved.

It is legitimate to hypothesize that orthogonal errors may reflect a hierarchical representation of the sloped environment, with locations at the same elevation grouped in the same spatial category. If this were the case, distinguishing among locations encoded in different categories would require less cognitive effort than distinguishing among locations within the same category. Evidence in support of hierarchical spatial representations has been collected for larger and more complex environments (Hirtle and Jonides 1985; McNamara et al. 1989), which challenges the idea of a unified cognitive map with preserved geometric properties. However, studies using slanted virtual environments (Kelly 2011; Restat et al. 2004; Weisberg and Newcombe 2014) have not examined this possibility, and the current paradigm used to investigate slope in the real world cannot address this issue.

A sloped environment that incorporates multiple target locations in a non-square enclosure (the walls of a square enclosure provide a reference frame parallel to the slope) may be particularly suited for examining the spatial and non-spatial information included in the representation. Specifically, the effort associated with traversing a sloped terrain may affect the clustering of spatial locations in memory. Given that terrain slope involves greater physical effort when moving along the vertical axis than the orthogonal one, a hierarchical representation that clusters objects at the same elevation might be used. This could lead to an overestimation of distances along the vertical axis and an underestimation of distances along the orthogonal axis. Future studies will have to assess this.

Conclusions

In a three-dimensional world with rich topography, vertically extended surfaces should not be ignored (for a review on navigation in 3D, see Jeffery et al. 2013). Terrain slope provides surface-traveling animals with a directional spatial cue that aids navigation in large-scale environments. However, only virtual environments have been tested (Chai and Jacobs 2009, 2010; Restat et al. 2004; Weisberg and Newcombe 2014); a real-world study has yet to confirm this. In small-scale environments, despite the fact that slope provides a rich context of sensory cues (vision and kinesthesia), slope-guided search significantly varies by sex, even in adults. The pervasive effect of sex is likely linked to spontaneous slope perception, as explicitly pointing out the slope to the participants does not eliminate the female disadvantage in performance (Nardi et al. 2011; Holmes et al. 2015). Conditions that significantly attenuate the sex gap should be examined so we may have a better understanding of this conspicuous sex difference, and of how slope is used.

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