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Up by upwest: Is slope like north?

Steven M. Weisberg¹, Daniele Nardi², Nora S. Newcombe¹, and Thomas F. Shipley¹

¹Department of Psychology, Spatial Intelligence and Learning Center, Temple University, Philadelphia, PA, USA

²Psychology, Sapienza Universita' di Roma, Rome, Italy

Terrain slope can be used to encode the location of a goal. However, this directional information may be encoded using a conceptual north (i.e., invariantly with respect to the environment), or in an observer-relative fashion (i.e., varying depending on the direction one faces when learning the goal). This study examines which representation is used, whether the sensory modality in which slope is encoded (visual, kinaesthetic, or both) influences representations, and whether use of slope varies for men and women. In a square room, with a sloped floor explicitly pointed out as the only useful cue, participants encoded the corner in which a goal was hidden. Without direct sensory access to slope cues, participants used a dial to point to the goal. For each trial, the goal was hidden uphill or downhill, and the participants were informed whether they faced uphill or downhill when pointing. In support of observer-relative representations, participants pointed more accurately and quickly when facing concordantly with the hiding position. There was no effect of sensory modality, providing support for functional equivalence. Sex did not interact with the findings on modality or reference frame, but spatial measures correlated with success on the slope task differently for each sex.

Keywords: Spatial memory; Spatial reference frames; Slope or slant; Sensory modality; Sex differences.

Consider navigating with a compass versus a portable global positioning system (GPS). A compass specifies the direction of magnetic north, regardless of the direction one faces. In contrast, many GPS systems rotate the map so that the user's facing direction is always up (i.e., forward). The compass provides an environment-relative spatial cue while a heading-up map provides an observer-relative cue. While both types of spatial cues can be used, one cue is often preferred over the other (Burgess, 2006). The present paper considers which representation is preferred in the case of terrain slope, a salient and effective spatial cue, yet one for which little is known about the nature of the

cognitive representation. Is slope used like a compass, with a natural conceptual north from which to calculate other directions? Or is slope used like a portable GPS map, variable and dependent on one's facing direction?

The direction of sloped terrain is a strong and salient gradient cue that provides the navigator with directional information. Olfactory cues and distal visual landmarks—for example, moving away or towards an odour or distal landmark—also provide directional information (Jacobs & Schenk, 2003). Unlike those cues, however, the salience of the vertical coordinate in space is highlighted in 3D environments by multiple sensory

Correspondence should be addressed to Steven M. Weisberg, Department of Psychology, Temple University, Philadelphia, PA 19122, USA. E-mail: smweis@temple.edu

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modalities. As evidence for slope's salience, when human adults encode the location of an object in a small, tilted enclosure, they tend to confuse locations at the same elevation more than locations at different elevation, suggesting that the target is encoded mainly by its position along the vertical axis (i.e., up or down; Nardi, Newcombe, & Shipley, 2011). The vertical axis has endpoints that are clearly labelled in most languages ("uphill" and "downhill"). In fact, it is noteworthy that some languages (e.g., Mayan Tzeltal spoken in a mountainous region of southern Mexico) use an absolute spatial system based on the prevailing slope, with directional terms equivalent to uphill and downhill, whereas the orthogonal axis is labelled "across" on both ends (Brown, 2008; Brown & Levinson, 1993).

Slope cues are highly salient, but the nature of the representation is unclear. The primary purpose of this paper is to determine the spatial reference frame spontaneously engaged by slope. Spatial reference frames typically engage a preferred orientation (orientation dependency; e.g., Diwadkar & McNamara, 1997; Presson, DeLange, & Hazelrigg, 1989; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998), which is responsible for the alignment effect (Levine, Jankovic, & Palij, 1982)—that is, a facilitation of retrieval of spatial memory when facing a particular orientation in the environment. If this preferred orientation is stable with respect to the external environment, we refer to the underlying representation with the general term environment-relative (or in the case of the slope cues used in this study, slope-relative). If the preferred orientation is stable with respect to the observer's viewpoint when learning the environment, we refer to the underlying representation as observer-relative. The distinction between environment-relative and observer-relative can be restated using a simple example. When navigating through an environment, individuals encode goals using a representation that has a certain orientation. That orientation could be with respect to the direction they are currently facing (e.g., toward the goal like the arrow on a portable GPS device) or with respect to a salient environment-based cue that

establishes a stable direction in the environment (e.g., toward a lake that is a very long distance away). The orientation of the representation can then be characterized in the first case as a variable vector—that is, depending upon the facing direction of the navigator, which depends on the location of the goal as the navigator moves through space. In the second case, the orientation can be characterized as a relatively constant vector—that is, depending upon the direction toward the lake (see Gramann, Müller, Eick, & Schönebeck, 2005, for a similar conceptualization). The former representation is then relative to the orientation of the observer (observer-relative), the latter relative to a stable property of the environment (environment-relative).

In flat environments, studies have provided evidence that humans use both types of reference frames (Burgess, 2006). Some studies have shown a preference for using observer-relative reference frames (e.g., Kelly & McNamara, 2009; Sholl, 1999; Wang & Spelke, 2000; Werner & Schmidt, 1999). However, this could be due to the low salience of the environmental reference systems sometimes used in the experiments (e.g., alignment with walls or with arrays of objects; see Shelton & McNamara, 2001). Other studies have shown that spatial reference frames can be defined by environment-relative cues like the intrinsic structure of an environment (Marchette, Yerramsetti, Burns, & Shelton, 2011). In familiar, flat environments, the preferred orientation is south-to-north (Frankenstein, Mohler, Bühlhoff, & Meilinger, 2012) and this orientation may be why north is implicitly associated with the top of a map (Brunye et al., 2012; Brunye, Mahoney, Gardony, & Taylor, 2010).

Prior research on slope cues has placed non-slope-based environmental cues in conflict with slope-based cues, but has not examined the reference frame used by slope alone. Results of the conflict studies have been mixed. Using immersive virtual reality, Kelly (2011) had participants learn a layout of objects on a sloped table in a rectangular room through different orientations and subsequently examined the reference frame used. Contrary to reorientation studies on pigeons,

which show a dominance of slope over geometric information (Nardi & Bingman, 2009; Nardi, Nitsch, & Bingman, 2010), results on humans revealed that the spatial reference frame was selected relative to the observer's first-learned perspective (Kelly, 2011). Nardi, Newcombe, and Shipley (2013) placed directional slope cues (the same environment as that used in the current study) directly in conflict with local landmark cues at each corner. The configuration of these landmarks was preserved, but they were rotated by 90°. Participants could choose the goal location based on conflicting information—either according to the slope, or according to the configuration of landmarks. Even when environmental landmark cues were available, a large set of participants (approximately 50%) chose to use the slope information.

The focus of the present study is different. When participants have no choice but to use slope cues, how is the directional slope represented? Is it malleable, and dependent on the individual's facing direction? Or is it stable, and independent of the individual's facing direction? We tested the following competing hypotheses when directional slope is the only available cue (see Figure 1). If the representation of slope is observer-relative, the preferred orientation should not be fixed relative to the environment, but will be determined based on the observer's experience during the learning phase. In particular, remembering a target could occur as a participant faces towards that vertical direction (whether uphill or downhill), such that the participant may choose that as the preferred direction during encoding on each trial. If the representation is slope-relative, there are two possible representations, each with a distinct preferred orientation (or valence). The preferred orientation could be downhill-to-uphill. Studies have indicated that the concept of uphill (increase in elevation) is implicitly associated with the concept of geographical north (Brunye et al., 2012; Brunye et al., 2010), making uphill more likely to be at the top of the cognitive map. On the other hand, the preferred slope-relative orientation could be uphill-to-downhill, as many vantage points use this point of view to depict space, and in general the downhill view

allows one to see more of an environment simultaneously than an uphill view (e.g., Steinberg, 1976), potentially aligning downhill with the top of the cognitive map. A slope-relative reference frame could be selected during learning as well. For example, a participant may align his body with uphill consistently throughout learning in order to represent the target's position relative to the slope, regardless of where it was hidden.

Given that Kelly's (2011) findings were obtained in a virtual environment with only visual cues, we also wondered if the effect was sensory-modality specific. What would happen if the slope was experienced in a real-world set-up, with visual and kinaesthetic sensory inputs? Despite providing distinctive sensory information, differences in the slope representations created by one sensory modality or another have not been much studied. A great deal of research has shown that input from various sensory modalities, including but not limited to vision, can be used to form representations that are effective for navigational success (e.g., Berthoz, Israel, Georges-Francois, Grasso, & Tsuzuku, 1995; Etienne & Jeffery, 2004; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Loomis, Klatzky, & Golledge, 2001; Walker & Lindsay, 2006). However, there is scant research on differences in the resulting representations. A few studies have compared visual with nonvisual information derived from language (Avraamides, Loomis, Klatzky, & Golledge, 2004), haptic (e.g., Giudice, Betty, & Loomis, 2011; Giudice, Klatzky, & Loomis, 2009; Levine et al., 1982), or proprioceptive exploration of object location (Yamamoto & Shelton, 2005), and evidence seems to indicate that learning from different encoding modalities builds a common spatial representation, which functions equivalently and supports equivalent spatial behaviour and performance. This finding has been referred to as functional equivalence (Bryant, 1997; Loomis, Klatzky, Avraamides, Lippa, & Golledge, 2007). Slope encoding provides a good test for the theory of functional equivalence because it is an ecologically relevant cue that can be perceived through two basic classes of modality: vision and kinaesthesia.

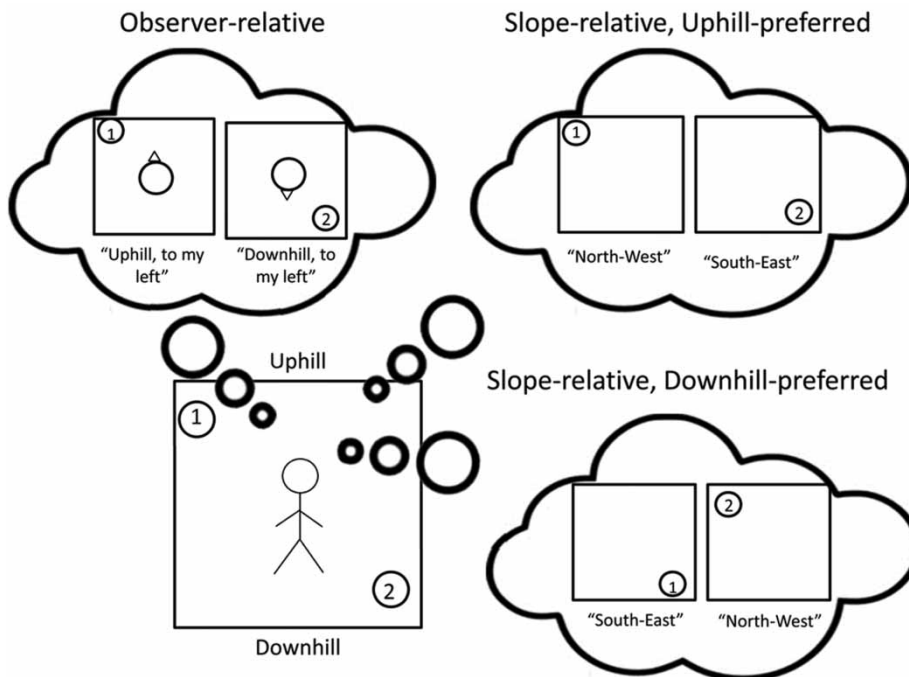


Figure 1. Observer-relative versus slope-relative representations for the goal location task. The square represents a bird's-eye view of the enclosure; the small circles represent the goal location on two separate trials. Each thought bubble is meant to describe a different possible representation (i.e., they do not occur within one participant simultaneously, but are distinct alternatives). As the participant encodes the environment (bottom square), three potential representations are indicated by thought bubbles. The left thought bubble depicts how the observer-relative representation of slope varies based on where the goal is hidden (i.e., determined by the direction in which the participant is facing when encoding the goal). If slope is represented this way, the participant should be fastest and most accurate when they are facing in the direction that the target is hidden. The two right thought bubbles demonstrate how the slope-relative representation does not vary based on the goal. The upper-right thought bubble depicts the uphill-facing orientation while the lower-right thought bubble depicts the downhill-facing orientation. The terms "north/east/south/west" connote directional information in terms of the environment itself, independent of observer viewpoint and relative terms like "left/right". If slope is represented this way, the participant should be fastest and most accurate when facing his preferred direction, regardless of where the goal is hidden.

We used a square, tilted enclosure, identical to the one used in Nardi et al. (2011; see Figure 2). Unlike the previous studies in which some participants did not notice or use the slope cues, we wanted to ensure that all participants at least attempted to use the slope to encode the goal. We thus drew participants' attention to the slope, had them walk around the enclosure, and, if they still did not notice the sloped floor, explicitly described the slope until they noticed it. After learning in which of the four corners a target was hidden, subjects had to point to the target while facing either uphill or downhill. Systematically varying where

the target was hidden relative to the participant's facing direction allowed us to describe whether the spatial reference frame used by the participant was observer-relative or slope-relative. If participants were faster and more accurate when the target hiding position and facing direction were aligned (concordant) than when they were misaligned (discordant), this would be evidence in favour of an observer-relative representation. If, instead, participants were faster and more accurate when facing a particular direction (e.g., uphill) regardless of where the target was hidden, this would be evidence in favour of a slope-relative representation.

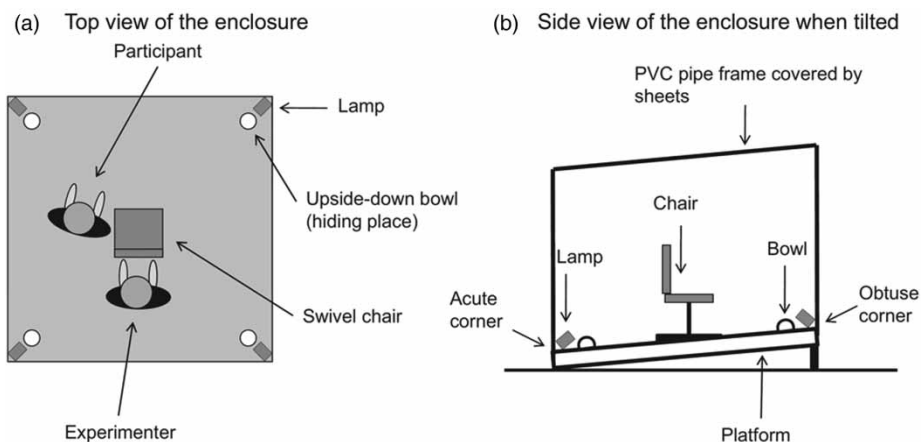


Figure 2. Depiction of sloped enclosure. Top view (left) and side view (right) of the enclosure used in the experiment. The slope of the floor was 5° above horizontal. The position of the target was entirely ambiguous with the exception of how it was positioned relative to the slope of the platform. From “The World is not Flat: Can People Reorient Using Slope?”, by D. Nardi, N. S. Newcombe, and T. F. Shipley, 2011, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37, p. 356. Copyright 2011 by the APA. Reprinted [or Adapted] with permission.

To determine whether this representation varied by the sensory modality of encoding, we had three modality conditions: visual-only, kinaesthetic-only, and a combined condition in which both senses were available. In addition, previous research on slope has uncovered a puzzling gender difference such that men significantly and consistently outperform women on tasks involving spatial reorientation with slope (Nardi et al., 2011). The Water Level Test and Spatial Orientation Test were administered in a previous study (Nardi et al., 2013) and were shown to correlate with encoding of slope or landmark cues, respectively. We decided to include a battery of spatial measures to investigate whether and how sex differences related to the use of slope cues could be explained by different patterns of spatial ability. The sex difference may not occur in performance on the slope task when attention is explicitly drawn to slope, as it was here. So we also administered tests of spatial perception (the Water Level Test), mental rotation, spatial visualization (the Spatial Orientation Test), and a self-report measure of navigation ability (Santa Barbara Sense of Direction) to determine whether slope cue use had distinct correlates for men and women.

Method

Apparatus

Enclosure. The apparatus was the same as the one used in Nardi et al. (2011). The experimental enclosure measured 244×244 cm and was 203 cm high (see Figure 2); it was placed inside a room measuring 290×460 cm and 250 cm high. The floor of the enclosure consisted of a wooden platform (244×244 cm, 12 cm thick), covered by grey carpet. White sheets on a PVC pipe frame composed the walls and the ceiling of the enclosure. The enclosure was tilted at an inclination of 5° (same inclination as that used in Nardi et al., 2011). On the floor of the enclosure, in each corner, there was a 25-W 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 with footrest was placed in the centre of the enclosure (base: 56 cm of diameter; total height: 110 cm). 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 base of the chair and the wedge. It is important to note that, when subjects were spinning on the swivel chair, their feet never touched the floor, so no cues were available for keeping track of their position relative to the slope.

Pointing device. We created a pointer for participants to use to point to the corner in which the target was hidden. Because reaction time was a key measure in this study, we wanted to avoid the bias for pointing in front compared to pointing behind that exists when using an arm to point (Franklin, Henkel, & Zangas, 1995; Yamamoto & Shelton, 2005). To that end, we used a 29-cm × 29-cm piece of foam board that could be held in the lap, and on which we attached an arrow that could be spun with one hand. We drew orthogonal lines on the board to divide it into four quadrants. Participants' response to each trial was recorded as the quadrant of the arrow relative to the direction the participant was facing.

Participants

Thirty-nine female and 38 male undergraduates from Temple University participated in the experiment. Five participants (three women and two men) were excluded from the analysis because, during debriefing, they reported attempting to use cues other than slope to remember the location of the goal. Because previous research with this enclosure found that participants were at chance performance on the task when slope cues were not present (i.e., when the floor of the enclosure was flat; Nardi et al., 2011), and no other participants reported using anything but slope cues, we dismissed the five participants for not following instructions. This left a total of 36 men and 36 women. The average age of participants was 22.40 years ($SD = 4.66$). Participants were randomly assigned (with the constraint that each group had equal number of men and women) to create groups of 24 participants (12 men and 12 women) in each of three conditions: visual (V), kinaesthetic (K), or combined (C; visual and kinaesthetic cues). Participants were recruited via an online system and received course credit, or via flyers posted around campus and received \$10.

Participants were told to wear comfortable shoes and to bring contacts or glasses if needed. In addition, participants were asked whether they weighed over 200 lb, in which case they were told they would have to be excluded on the basis of equipment limitations (no participants reported weighing over 200 lb).

Procedure

Goal location task. Upon arriving, participants were told they would be participating in a spatial experiment. They were told their task was to remember where an object was hidden inside an enclosure and later point to that object. Participants read and signed an informed consent form and went to a room in a different part of the building for the experiment. Participants were blindfolded and led by the experimenter into the room where they sat on a swivel chair in the centre of the enclosure. The experimenter adjusted both the curtains surrounding the enclosure and a cloth placed under the chair. After the enclosure was set up, the experimenter slowly spun (5 rpm) the participant around in the chair to ensure he could not use the entrance to the enclosure as a point of reference. The chair was positioned on a wedge to ensure no slope could be felt while seated. The experimenter then asked the participant to stand up and remove the blindfold. The participant always first stood up on one side of the room, with uphill on his left while facing the centre of the enclosure, to ensure the first exposure was neither facing uphill nor facing downhill.

The experimenter then drew the participant's attention to identical bowls in each of the four corners of the enclosure and told the participant to remember under which bowl the target (a \$1 bill) would be hidden. The experimenter prompted the participant to walk around the enclosure and to try to notice anything peculiar about the enclosure that could help in remembering where the target was hidden. If the participant reported noticing the slope, she was asked to point which direction was uphill. If the participant did not notice anything, the experimenter asked the participant to pay attention to the floor until the participant noticed the slope and pointed to uphill. The

experimenter remarked that the participant should use only the slope of the floor to remember the target location because it was the only useful cue. The experimenter then told the participant the sequence of events for each trial. The participant completed a practice trial, in which the encoding portion was carried out, and was also shown how to use the pointer in the pointing portion of the task. The participant was instructed to point to the target location (one of the corners of the enclosure) immediately after being told whether he faced uphill or downhill. These directions were demonstrated using the chair so the participant saw that, for example, “uphill” meant facing the steepest uphill direction. The experimenter addressed any questions and ensured that the participant understood the whole procedure.

The experimenter spun the participant around in the chair several times, then stopped the participant in front of one of the four corners (the one in which the target was hidden). The experimenter hid the target after the participant stopped spinning, but before the participant stood up from the chair or took off the blindfold. Then, depending on the condition, the participant was instructed to: (a) take off the blindfold but remain seated (visual: V), (b) stand up but keep the blindfold on (kinaesthetic: K), or (c) stand up and take the blindfold off (combined: C). In the V and C conditions, the experimenter pointed to the corner in which the target was hidden. In the K condition, the participant walked with the aid of a stick; the target location was shown by the experimenter holding the other end of the stick and tapping it on the hiding location. In the C and K conditions, participants could walk around to have a better perception of the slant, but they always had to keep one hand on the back of the chair. In the V condition, participants were slowly rotated on the chair (5 rpm) by the experimenter, so that they could view the enclosure. Regardless of condition, the experimenter timed from the moment the participant learned where the target was hidden until the participant said “Done”. The participant had as long as they needed to encode where the target was hidden, but was also told he would be timed for research purposes.

When the participant was finished encoding, the participant was instructed to sit back in the swivel chair and put the blindfold back on. From this point on, the procedure was identical for all conditions. During the subsequent disorientation, the participant was spun around, varying speed and direction, while performing a shadowing task. This task was implemented to prevent the participant from using a verbal algorithm that bypasses the need for spatial representation (i.e., “If I am facing uphill, point right; if I am facing downhill, point left”). The shadowing task involved counting aloud backward from a three-digit number by an integer between two and five (e.g., “Count backward from 350 by 3”). Pilot testing revealed this task to be challenging enough to require conscious verbal processing. After approximately one minute of being spun, the experimenter stopped the participant from spinning (either uphill or downhill), interrupted the participant’s counting, handed them the pointer, and said: “Point to the target, knowing that you are facing uphill (or downhill)”. Reaction time was recorded from the moment the experimenter told the participant which direction she was facing until the participant said “Done”. The corner of the room corresponding to the quadrant of the pointer was recorded. Each participant completed four experimental trials. No feedback was provided throughout the duration of the experiment. During the four trials, the target location varied across all possible corners, in pseudorandom order, with the constraint that the target could not be uphill (or downhill) for two consecutive trials. The initial target location was counterbalanced across sex within each condition. Furthermore, the order of concordant or discordant trials and facing-uphill or facing-downhill trials was counterbalanced across sex within each condition.

As a control to ensure that our device reduced the bias in pointing in front compared to behind (Franklin et al., 1995; Yamamoto & Shelton, 2005), after the four experimental trials, the experimenter asked the participant to imagine sitting in the driver’s seat of a car. While blindfolded and after disorientation (just like in the experimental trials), in two consecutive trials the participant

was asked to point to either the steering wheel (in front) or the trunk (in back) of the car (in counter-balanced order). If our pointing device elicited a pointing bias, reaction time in these pointing judgements should have differed.

Spatial measures

Spatial Orientation Test. The Spatial Orientation Test (SOT; Kozhevnikov & Hegarty, 2001; we used the revised version by Hegarty & Waller, 2004) requires viewing an array of objects on a piece of paper, taking the perspective of standing next to one object and facing another, with the task of pointing to a third object. Five minutes are allowed to complete the 12-item measure. The angle between the correct answer and the participant's response is recorded for each item and averaged to yield an overall error score. The SOT measures the participant's ability to egocentrically reorient in an array and is distinct from spatial visualization as measured by mental rotation (Hegarty & Waller, 2004).

Mental Rotation Test. The Mental Rotation Test (MRT; Vandenberg & Kuse, 1978; adapted by Peters et al., 1995) is a measure of spatial visualization, which consists of items made up of one target form composed of a number of cubes. Participants must choose the two (out of four) objects that correspond to the target after being rigidly rotated. A response was considered correct only if participants chose both correct items. The MRT consists of two parts of 10 items each, with 3 min allotted for each part of the test. The MRT measures the participant's spatial visualization ability, which requires imagining how an object would look if it were rotated.

Water Level Test. The Water Level Test (WLT; Piaget & Inhelder, 1956; we used the test devised by Vasta & Liben, 1996) is a spatial perception measure with displays of bottles tilted diagonally. The participant's task is to draw what the water level in each bottle would look like. Since water levels are always horizontal, the angle of divergence

from 0° (measured from a horizontal reference line just below each bottle) is recorded. Scores range from 0 to 2 for each item, with 0 indicating that the participant's response was off by more than 10°, 1 indicating that the response was off by 5 to 10°, and 2 indicating that the response was within 5° of horizontal. The WLT requires participants to visualize the water level in a tilted bottle, assuming gravity is acting toward the bottom of the page.

Santa Barbara Sense of Direction scale. The Santa Barbara Sense of Direction scale (SBSOD; Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) consists of 15 items, which participants respond to on a 7-point Likert scale. The scale is designed to measure how strong a navigator a participant feels she is, with lower scores indicating lower navigation ability. The SBSOD has been shown to be correlated with a variety of real-world spatial navigation tasks including spatial reorientation and learning a spatial layout (Hegarty et al., 2002).

Results

Error rates

Overall, participants found the goal in 71.88% of trials ($SD = 29.35$), well above chance (25%), one-sample $t(71) = 13.55$, $p < .001$. We first analysed error rates to assess effects of gender differences and modality condition. When both cues were available (combined condition), men ($M = 79.17\%$, $SD = 23.44$) and women ($M = 75.00\%$, $SD = 30.15$) did not make a significantly different number of correct responses, $t(22) = 0.38$, $p = .71$, $d = 0.16$. Because the current task explicitly instructed participants to use slope to encode the location of a goal, this result is not contradictory to previous work describing sex differences (Nardi et al., 2011). A 2×2 between-subjects analysis of variance (ANOVA) with the single-modality encoding conditions (visual vs. kinaesthetic) and sex (men vs. women) revealed no main effects or interactions, all $ps > .25$.¹ Based on these null

¹A 2 (gender) by 3 (condition) ANOVA also reveals no main effects or interactions.

| Total | Raw Errors | | | Contrasts | | |
|----------------|------------|----------|----------|-----------------|--------------|-----------|
| | Orthogonal | Vertical | Diagonal | O-V | O-D | V-D |
| Discordant | 35 | 4 | 10 | $p = .000005^*$ | $p = .001^*$ | $p = .09$ |
| Concordant | 9 | 10 | 13 | $p = .83$ | $p = .55$ | $p = .66$ |
| Total | 44 | 14 | 23 | $p = .00017^*$ | $p = .018$ | $p = .13$ |
| Males | | | | | | |
| Discordant | 15 | 2 | 5 | | | |
| Concordant | 3 | 6 | 7 | | | |
| Total | 18 | 8 | 12 | | | |
| Females | | | | | | |
| Discordant | 20 | 2 | 5 | | | |
| Concordant | 6 | 4 | 6 | | | |
| Total | 26 | 6 | 11 | | | |

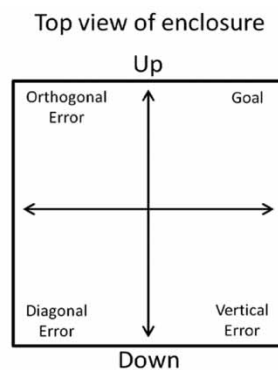


Figure 3. Errors in goal location task by trial type, sex, and error type. An analysis of error types shows that participants were far more likely to make an orthogonal error than a slope-based error (i.e., choosing a downhill location when the target was hidden uphill, regardless of position on the left–right axis) in discordant trials than in concordant trials. This pattern obtained for both sexes. Contrasts were Wilcoxon signed-rank tests, with significance values Bonferroni corrected $\alpha = .05/9 = .0055$; $p < .0055$.

effects, we collapsed across modality condition and sex for the subsequent analyses that focus on the question of reference frame selection.

Recall that an effect of facing direction would provide evidence for a slope-relative representation as this would reveal a preference for one fixed direction, whereas an effect of concordance would provide evidence for an observer-relative representation. We analysed the error data by trial type (concordant or discordant; facing uphill or facing downhill), applying a Bonferroni correction to adjust the family-wise error rate $\alpha = .05$ ($\alpha = .05/5 = .01$). Figure 3 displays the raw number of errors by alignment (concordant or discordant). Overall, participants committed significantly fewer errors in concordant trials (32) than in discordant trials (49), Wilcoxon $Z = 2.60$, $p < .01$. Parsing the trials by facing direction revealed that participants committed a similar amount of errors in facing downhill (42) and facing uphill (39) trials, Wilcoxon $Z = 0.47$, $p = .64$.

Analysing the types of errors that participants made based on trial type provided further insight into the reference frame question. Figure 3 shows the experimental environment where the three incorrect corners have been labelled according to a position of the goal in the corner that is uphill on the right. The raw numbers of errors committed to each corner are reported. Errors were analysed through comparisons between pairs of incorrect

Table 1. Raw number of errors by trial type

| Facing direction | Orthogonal | Vertical | Diagonal | Total |
|------------------|------------|----------|----------|-------|
| Facing up | 21 | 6 | 12 | 39 |
| Facing down | 23 | 8 | 11 | 42 |
| Total | 44 | 14 | 23 | 81 |

Note: The error types did not vary systematically between facing-uphill and facing-downhill trials.

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 Figure 3. Of the three types of possible errors (vertical, orthogonal, and diagonal), the most common was the orthogonal error—that is, incorrectly recalling the position of the goal along the horizontal axis (left–right) of the slope; however, this occurred only during discordant trials and not in concordant trials. When error rates are compared between facing-uphill and facing-downhill trials, the pattern of results is the same for both of them (see Table 1). In both trial types, participants were most likely to commit orthogonal errors.

Reaction time

To allay concerns about natural bias for pointing toward the front, we used the same protocol as

that for the goal location trials but asked participants to imagine sitting in the driver's seat of a car. The difference in reaction time (RT) when pointing to the trunk and the steering wheel was not significant, $t(71) = 1.26$, $p = .21$, $d = 0.30$. In fact, participants were slightly, but not significantly, quicker to respond when pointing to the trunk ($M = 3.91$, $SD = 2.32$) than to the steering wheel ($M = 4.35$, $SD = 3.34$), the reverse, albeit non-significant, pattern from what would be expected if participants exhibited a bias toward pointing to the front. This suggests that the quicker response in concordant trials cannot be ascribed to a faster motoric response when pointing the dial in front as opposed to the back.

RT was analysed with a mixed $2 \times 3 \times 2 \times 2$ ANOVA, with sex (men or women) and condition (V, K, or C) as between-subjects factors, and alignment (concordant or discordant pointing) and facing direction during pointing (uphill or downhill) as within-subject factors. Overall, RT was significantly different between concordant and discordant pointing (main effect of alignment), $F(1, 66) = 4.47$, $p = .038$, $\eta^2 = .06$. RT was not significantly different between facing uphill or downhill (no main effect of facing direction), $F(1, 66) = 2.03$, $p = .15$, $\eta^2 = .03$ (see Figure 4). Furthermore, there was no main effect of encoding condition, $F(2, 66) = 0.46$, $p = .64$, $\eta^2 = .01$. However, there was a main effect of sex, with men significantly faster than women in responding, $F(1, 66) = 9.85$, $p = .003$, $\eta^2 = .13$. The only significant interactions were the sex by facing direction, $F(1, 66) = 4.28$, $p = .04$, $\eta^2 = .06$, and the sex by facing direction by condition, $F(2, 66) = 3.99$, $p = .02$, $\eta^2 = .11$; for all other interactions, $ps > .12$.² To determine the nature of the sex-by-facing-direction interaction, we computed Sidak corrected follow-up contrasts. The sex-by-facing-direction interaction was driven by the finding that men were significantly slower to respond to downhill-facing trials ($M = 8.09$,

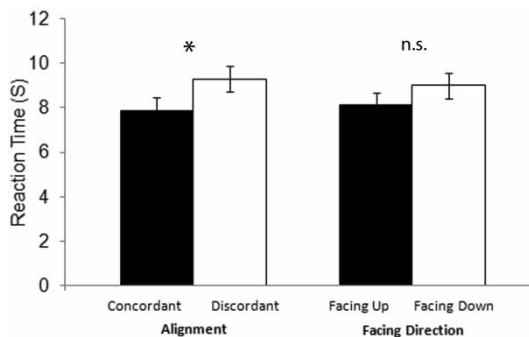


Figure 4. Reaction time difference by trial type (alignment or facing direction). Reaction time was significantly different when comparing concordant with discordant trials (left cluster), but was not significantly different when comparing facing direction (up vs. down, right cluster). * $p < .05$. ns = not significant. Error bars = ± 1 SEM.

$SD = 5.68$) than to uphill-facing trials ($M = 5.90$, $SD = 2.73$), $t(34) = 2.58$, $p < .05$. Women did not differ on RT between downhill trials ($M = 10.00$, $SD = 5.68$) and uphill trials ($M = 10.40$, $SD = 5.88$), $t(34) = 0.46$, $p > .05$. To follow up on the sex-by-facing-direction-by-condition interaction, we computed Sidak corrected follow-up contrasts between facing-uphill and facing-downhill trials for each gender within each condition. The only significant contrast was for male participants in the combined condition who took significantly longer to respond to facing-downhill than to facing-uphill trials, $t(34) = 3.14$, $p < .05$. All other contrasts were not significant.

We conducted several follow-up analyses to determine whether RT revealed an overall tendency for observer-relative or slope-relative representations. First, we looked at participants who had success on the goal location task. To do this we excluded from analysis participants who performed at chance (committing 3 or more errors out of 4 pointing judgements; a total of 11 subjects out of 72: 5 men and 6 women). Considering only participants who recalled locations successfully, the same

²The analyses were repeated with outliers (more than 2 standard deviations above the mean) removed, and the results were identical with the exception of a significant Sex \times Facing Direction \times Alignment \times Condition interaction, and no Sex \times Facing Direction \times Condition interaction. Because of the lack of theoretical interest in either the three- or four-way interaction, the analyses are functionally identical.

pattern was found: There was a main effect of alignment, $F(1, 55) = 5.44$, $p = .02$, $\eta^2 = .09$, and no main effect of facing direction, $F(1, 55) = 0.74$, $p = .37$, $\eta^2 = .01$. Participants performing better than chance were faster in concordant pointing than in discordant pointing, suggesting they recruited an observer-relative strategy.

We also wanted to eliminate the possibility that the longer response time in discordant trials is attributable to the greater number of errors in those trials than in concordant ones, especially because correct trials had significantly faster RT than incorrect trials. Among participants who both committed errors and responded correctly, a paired-sample t test revealed that RT for correct trials was significantly faster than that for incorrect trials, $t(40) = 2.14$, $p = .04$.³ We conducted a paired-sample t test to evaluate whether RT was faster for correct concordant trials than for correct discordant trials among participants who responded correctly to at least one concordant and at least one discordant trial. Concordant trials were still responded to more quickly than discordant trials, excluding incorrect trials, $t(55) = 3.20$, $p = .002$.⁴ Conversely, excluding incorrect trials in the same manner, there was no significant difference in RT between target-uphill and target-downhill trials, $t(58) = 1.25$, $p = .22$, or between facing-uphill and facing-downhill trials, $t(56) = 1.18$, $p = .24$. This further suggests observer-relative encoding of the goal.

We also did not find individual biases suggestive of slope-relative encoding. Figure 5 represents, for each participant, the difference in RT when the trial is concordant or discordant, and when the facing orientation at retrieval is uphill or downhill. The data suggest a normally distributed range of difference scores centred on a mean of zero, suggesting no individual bias such that some participants were fastest when facing uphill while others were fastest when facing downhill. If

individual participants were biased toward the goal being uphill or downhill, or facing uphill or downhill, a bimodal distribution would be expected.

Encoding time

A 2 (sex) \times 3 (condition) between-subjects ANOVA revealed a significant effect of condition, $F(2, 66) = 8.97$, $p < .001$, $\eta^2 = .21$. There was no main effect for sex and no significant interaction ($ps > .05$). Follow-up, post hoc, pairwise contrasts (Bonferroni-corrected $\alpha = .0167$) revealed that the kinaesthetic condition significantly differed from both the visual condition, $t(46) = 3.04$, $p < .05$, and the combined condition, $t(46) = 3.56$, $p < .05$. Participants in the visual and combined conditions did not differ in encoding time (see Figure 6). This finding suggests that participants took substantially longer to encode the location of the goal when visual cues were removed, regardless of the presence of kinaesthetic information.

Spatial measures

Men outperformed women on the MRT, $t(70) = 3.51$, $p = .01$, $d = 0.84$, the SOT, $t(70) = 4.54$, $p < .001$, $d = 1.09$, and the SBSOD, $t(70) = 2.05$, $p = .04$, $d = 0.49$. Men scored numerically higher than women on the WLT, but this difference was not significant, $t(70) = 1.76$, $p = .08$, $d = 0.42$. Different patterns of results were obtained for correlations between the two sexes (see Tables 2 and 3). For men, the MRT was most strongly correlated with the number of correct answers in the goal location task, $r = .61$, $p = .000079$, while for women the correlation was not only nonsignificant, $r = .19$, $p = .27$, it was significantly lower than the correlation for men, $Z = 1.97$, $p = .048$. For women, the WLT correlated most strongly with the number of correct answers, $r = .45$, $p = .006$, while for men WLT was not significantly correlated, $r = .24$, $p = .16$. However, the difference between these two correlations was not

³Because many participants either responded correctly to all four trials, or committed errors on all four trials and were thus excluded from the paired-sample t test, we conducted an independent-samples t test between correct and incorrect trials. This test also revealed a significantly faster RT for correct trials, $t(286) = 5.38$, $p < .001$, $d = 0.64$.

⁴An independent-samples t test was conducted between concordant and discordant trials, excluding incorrect trials and yielded a significant effect of faster RT for correct concordant trials, $t(205) = 3.32$, $p = .001$, $d = 0.46$. Comparing goal-up versus goal-down trials and face-up versus face-down trials yielded nonsignificant differences, $p > .05$.

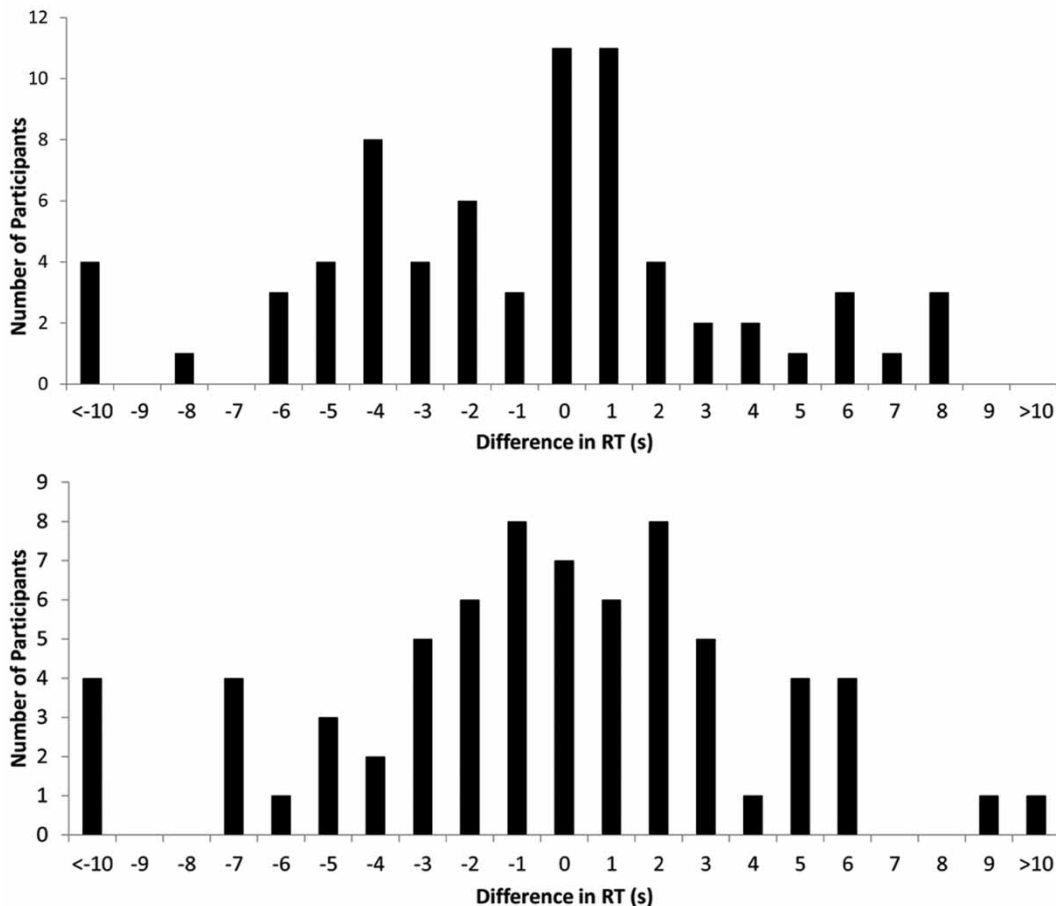


Figure 5. Difference in reaction time (RT) between concordant and discordant trials (top) and facing-up and facing-down trials (bottom). Histograms of difference scores in reaction time of individual participants for concordant minus discordant trials (top) and facing-up minus facing-down trials (bottom). In general, participants responded to concordant trials more quickly than discordant trials. No bias is evident, however, for participants responding more quickly to trials based on which direction the participant faced. The histograms also do not follow bimodal distributions, which would suggest that individual participants had biases for trial types other than concordant/discordant.

significant, $Z = 0.91$, $p = .36$. The SOT (higher scores indicating larger error) was significantly negatively correlated with performance for men, $r = -.44$, $p = .008$, but not for women, $r = -.30$, $p = .08$. These correlations were not significantly different from each other, $Z = 0.62$, $p = .54$. The SBSOD was not significantly correlated with performance for either men, $r = -.07$, $p = .70$, or women, $r = .29$, $p = .10$. Overall, the psychometric measures (except SBSOD) were significantly correlated with reaction time on the goal location task for men but not for women.

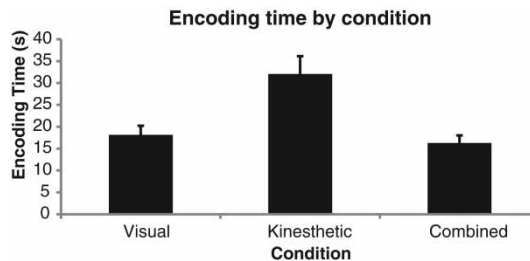


Figure 6. Encoding time by sensory modality condition. Encoding time took significantly longer in the kinesthetic condition compared to the combined, and visual condition. No other contrasts were significant. (Error bars = ± 1 SEM).

Table 2. Correlations between psychometric measures and goal location task

| Variable | MRT | WLT | SOT | SBSOD | Correct trials |
|-----------------------|---------------|---------------|---------------|-------------|----------------|
| MRT | — | | | | |
| WLT | .32** (.27) | — | | | |
| SOT | -.45** (-.33) | -.43** (-.38) | — | | |
| SBSOD | .16 (.08) | .12 (.07) | -.21 (-.12) | — | |
| No. of correct trials | .44** (.46) | .32** (.32) | -.32** (-.33) | .11 (.10) | — |
| Reaction time | -.34** (-.23) | -.25* (-.20) | .38** (.26) | -.21 (-.15) | -.36** (-.37) |

Note: MRT = Mental Rotation Test; WLT = Water Level Test; SOT = Spatial Orientation Test; SBSOD = Santa Barbara Sense of Direction. This pattern of results does not change when the reaction time for correct trials only is used. Values controlling for sex in parentheses.

* $p < .05$. ** $p < .01$.

Table 3. Correlations between spatial measures and slope goal location tasks by sex

| Variable | MRT | WLT | SOT | SBSOD | Correct trials |
|----------------|-------|-------|-------|-------|----------------|
| Women | | | | | |
| MRT | — | | | | |
| WLT | -.05 | — | | | |
| SOT | -.36* | -.36* | — | | |
| SBSOD | .18 | .21 | -.13 | — | |
| Correct trials | .19 | .45* | -.30 | .28 | — |
| Reaction time | -.13 | -.07 | .19 | -.20 | -.28 |
| Men | | | | | |
| MRT | — | | | | |
| WLT | .41* | — | | | |
| SOT | -.39* | -.51* | — | | |
| SBSOD | .02 | -.03 | -.10 | — | |
| Correct trials | .61* | .24 | -.44* | -.07 | — |
| Reaction time | -.36* | -.34* | .42* | -.08 | -.48* |

Note: MRT = Mental Rotation Test; WLT = Water Level Test; SOT = Spatial Orientation Test; SBSOD = Santa Barbara Sense of Direction. This pattern of results does not change when the reaction time for correct trials only is used. MRT and SOT correlate significantly with number of correct trials for men and, along with WLT, with reaction time. WLT is the only significant correlate of the number of correct trials for women.

* $p < .05$.

Discussion

Unlike north, slope is not represented with a stable, slope-relative reference frame. Instead, the representation of slope is characterized by an observer-relative reference frame, which is variable and depends upon the direction in which the sloped

environment is encoded. In this case, when a target was hidden in a square, sloped room, participants were faster and more accurate when they were facing the direction the target was hidden, regardless of whether that direction was uphill or downhill. If slope was represented with a conceptual north, we would have expected to find that participants would be faster and more accurate when facing in that preferred orientation (whether uphill or downhill), regardless of where the target was hidden. This occurred neither for individual participants nor in the aggregate.

There are several possible reasons participants do not spontaneously represent slope with a conceptual north. First, environments that are represented with stable extrinsic reference frames are often highly familiar—a college campus (Marchette et al., 2011), or one's home town (Frankenstein et al., 2012). Over time, a navigator may incorporate environment-relative cues into his spatial representation based on the organization of the environment, then perform better on spatial tasks that are aligned with those cues. The cue used in the present study, terrain slope, may be an unfamiliar spatial cue for which no preferred representation exists. Alternatively, experience with sloped environments may prompt an uphill-preferred representation in some cases, but a downhill-preferred representation in others, although analyses of individual biases revealed that this was not the case. Theoretically, though, either position is tenable. Participants may have preferred to represent sloped environments with uphill-as-north

based on findings that north is implicitly associated with uphill (Brunye et al., 2010) and is often seen at the top of maps. However, many canonical images are portrayed facing downhill (e.g., the New Yorker's "A View of the World from Ninth Avenue"), a direction that offers a richer vantage point. Practically, different environments may offer advantages to flexible navigators who can alter their use of slope as a directional cue depending on the direction they are currently facing. Finally, it is possible that observer-relative reference frames may interact with an observer's experienced views in an environment. For example, McNamara and colleagues had participants learn paths that were aligned or misaligned with structures around a college campus and found that, based on the different viewpoints that participants experienced during learning, participants' spatial reference frames were organized differently (McNamara, Rump, & Werner, 2003).

In the present study, because we were interested in spontaneous encoding of a goal location, participants were not restricted to learn the environment from specific viewpoints. Nevertheless, it is possible that the viewpoints they experienced led them to prefer an observer-relative reference frame. In the future, systematic variation of views should address this question directly. For example, our experimental paradigm does not examine the role of slope outside the experimental enclosure. It is unlikely that our experimental procedure altered an observer's use of slope in the larger environment because the slope of the university campus is negligible. Examining slope in this way would place an environmental cue, or "global slope" in conflict with an observer-based cue, or "local slope". It is possible that in a flat urban environment people will tend to focus on observer-relative frames of reference for local slopes. In contrast, people in a large-scale environment that is sloped may tend to use an environment-relative reference frame for slope.

In support of an observer-relative reference frame, we found fewer errors and faster reaction times for concordant than for discordant trials. We found in general no significant difference for downhill-facing trials compared to uphill-facing

trials in either reaction time or error rates, with one exception that we discuss below. Although it is possible that some participants had an uphill-facing preference, while others had a downhill-facing preference causing the errors to average out across the sample, the unimodal distribution of difference in reaction time for each participant between uphill-facing and downhill-facing trials is centred on 0 seconds difference (no preference), suggesting no such individual differences (see Figure 5). Note that the pattern of results predicted by our hypotheses can also be put in terms of front-facilitation (Kelly & McNamara, 2009). Reference frames exhibit a front-facilitation effect for both the orientation in which an array of objects was learned and an individual's present body-state. If the representation employed by participants was environment-relative, the facing direction "uphill" would have shown benefits while the facing direction "downhill" would have shown deficits (or vice versa) regardless of where the target was hidden. Instead, we found facilitation for the participant's facing direction during retrieval, regardless of whether that direction was uphill or downhill, similar to the effect found for egocentric retrieval (Kelly & McNamara, 2009).

Interestingly, the types of errors that participants made varied according to whether the trial was concordant or discordant. For discordant trials, participants were much more likely to make an orthogonal error than misremember whether the goal was uphill or downhill. However, for concordant trials, errors were fewer and equally split among orthogonal, vertical, and diagonal (i.e., participants committed errors randomly). Importantly, the pattern of error types did not change between facing-uphill trials compared to facing-downhill trials. The sharp increase for just orthogonal errors between concordant and discordant trials suggests that errors on discordant trials reflected interference between the preferred representation (facing toward the target) and the participant's current facing direction, and not a misrepresentation of the position of the target along the slope axis. In line with previous studies (Nardi et al., 2011), memory for the vertical coordinate of the goal is robust, and there is confusion only for the

horizontal (orthogonal) coordinate (Nardi et al., 2011).

In the current paradigm, the modality in which slope was encoded made no difference in the resulting representation. Our results are in agreement with other studies that have found evidence for the functional equivalence of sensory modalities for cognitive representations (i.e., the underlying cognitive representation is the same, regardless of the sensory modality that information is encoded in; Bryant, 1997). Research on spatial representations encoded haptically versus visually similarly demonstrate no differences in alignment effects on the basis of sensory modality, even among congenitally blind individuals who are unable to form visual representations (Giudice et al., 2011). In the current study, participants performed above chance in each modality condition, and there were no interactions between modality condition and reaction time, errors, or types of errors. The kinaesthetic condition had significantly longer encoding, a finding that can largely be attributed to the difficulty of moving around a small enclosure with a blindfold on. Future tests of the functional equivalence theory could vary sensory modality without explicitly mentioning slope, vary the dependent measure and type of task for which slope is required to be used, and vary the sensory information itself to make the slope more or less salient in one modality or the other. In the current study, the enclosure exactly matched the kinaesthetic cues that one would experience on a 5° slope in a natural environment, but the visual cues were relatively impoverished: The visual elements that normally emphasize the slant of the terrain—such as the horizon, trees, and walls—were few (only curtains) and inconspicuous (the curtains were homogeneously white). These cues are typically aligned and used together in the real world, but altering their salience and relevant validity in virtual environments would also be a fruitful line of investigation.

Whereas previous work with this enclosure found a sex difference in a reorientation task such that men consistently outperformed women when slope cues were available (Nardi et al., 2011), the current work changed a crucial aspect of the previous

methodology. Participants were explicitly told to use slope and had the opportunity to observe that slope was the only useful cue after completing the practice trial. We chose to mention slope to participants because, for this study, we were interested in the nature of the resulting representation given a particular cue, not whether participants spontaneously notice that cue. When slope cues are explicitly mentioned, gender differences in using slope as a cue as found previously (Nardi et al., 2011) are attenuated. In line with this, we only find a significantly faster RT for men, but not higher accuracy. The only other sex difference on the slope task observed in the present study was a sex-by-facing-direction interaction for RT such that men were faster to respond on facing-uphill trials than they were on facing-downhill trials. This finding did not suggest a reasonable interpretation, however, though future work should investigate whether different facing directions are preferred for men and women.

Psychometric data tentatively suggest sex differences in the strategy adopted by males and females. The fact that MRT and SOT scores were most predictive of the number of correct trials for men, whereas performance on the WLT was most predictive for women, suggests the intriguing possibility that men, but not women, are using a strategy that involves mental rotation—that is, representing the location of the goal according to their present viewpoint, then rotating that representation to align with the representation they encoded. On the other hand, women's performance depends more on their ability to represent the goal according to its location on the slope, a process limited by spatial perception as measured by the WLT. Such a representation could still have a preferred direction, which would facilitate performance (e.g., representing the goal as “if I am facing uphill, the goal is right; if I am facing downhill, the goal is left”). Thus, while both representations may be observer-relative, the strategies employed to solve the goal location task when the facing direction is misaligned with the preferred direction may differ by sex.

Unfortunately, while this hypothesis is intriguing, other patterns in the data do not support

this conclusion. First, while historically the WLT has shown persistent and robust sex differences in performance favouring men (Signorella & Jamison, 1978; Voyer, Voyer, & Bryden, 1995), a significant gender difference was not observed for the WLT in this study. Women's scores showed a normal distribution centred on the midpoint, while men's scores were bimodally distributed with some scoring at ceiling and others at floor. Nevertheless, there were no systematic differences between the low and high male WLT groups, and women scoring above and below the mean of WLT largely matched male performance on the goal location task.

Second, the WLT was untimed while the MRT and SOT were timed tests. Thus, although accuracy was stressed over reaction time, the similarity between the goal location task and MRT/SOT in terms of time pressure led to a correlation between them for men who also responded more quickly on the goal location task. The psychometric measures, MRT, WLT, and SOT, were significantly correlated with reaction time on the goal location task for men, but not women. Men may have had higher confidence than women in completing all of the spatial tasks, which could account for their faster reaction times on the goal location task overall. Recent research showed that women had lower confidence levels in completing a similar spatial task compared to men (Nardi et al., 2013). If that were the case here, the significant correlations might reflect, for men, a relationship between spatial ability and speed of performance. For women on the other hand, lack of confidence might have slowed down reaction time overall, dissociating that measure from spatial ability. This explanation could also account for the significant correlation between reaction time and number of correct trials for men and the lack of significance for the same correlation for women.

In summary, data from this study suggest that slope is primarily encoded and represented in an observer-relative fashion, regardless of sensory modality. Future research should determine whether other, possibly less salient, directional cues (e.g., visual, distal landmarks) are similarly

encoded with respect to the observer, the effect of facing directions that are not explicitly aligned with the vertical axis of the directional cue, and whether varying the salience and reliability of sensory information for different modalities modulates the way slope is used as a spatial cue.

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