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A slippery directional slope: Individual differences in using slope as a directional cue

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Abstract Navigators rely on many different types of cues to build representations of large-scale spaces. Sloped terrain is an important cue that has received recent attention in comparative and human spatial research. However, the studies to date have been unable to determine how directional slope information leads to more accurate spatial representations. Moreover, whereas some studies have shown that the inclusion of slope cues improves performance on spatial tasks across participants (Kelly, 2011; Restat, Steck, Mochnatzki, & Mallot, 2004), other research has suggested individual differences in the benefits of slope cues (Chai & Jacobs, 2010; Nardi, Newcombe, & Shipley, 2011). We sought to clarify the role of sloped terrain in improving the representation of large-scale environments. In Experiment 1, participants learned the layout of buildings in one of two desktop virtual environments: either a directionally sloped terrain or a completely flat one. Participants in the sloped environment outperformed those in the flat environment. However, participants used slope information as an additional cue, rather than as a preferred reference direction. In Experiment 2, the two virtual environments were again either flat or sloped, but we increased the complexity of the relations between the slope and the path. In this experiment, better performance in the sloped environment was only seen for participants with good self-reported senses of direction. Taken together, the studies show that slope provides useful information for building environmental representations in simple cases, but that individual differences emerge in more complex situations. We suggest that good and bad navigators use different navigational strategies.

Keywords Individual differences · Spatial navigation · Slope · Slant · Virtual environments

Consider navigating a section of San Francisco, a famously hilly city. San Francisco, like many gridded urban environments, offers the navigator the possibility of using relatively simple straight paths and right angles to remember spatial locations, but also offers strong additional spatial information in the form of directional slope. Presuming that one is navigating around an area with a single prevailing slope direction, if one walks uphill and turns right, turning left again will take one back in the uphill direction—the relation between the streets and the slope is constant, reinforcing, and changes systematically and categorically at right angles. Contrast the urban case with a path through a local park. The park path may lead up a hill, but it may veer and curve, continuously varying the alignment between the direction of the path and the direction and steepness of the slope.

Due to its high ecological validity, slope has been recently studied by cognitive and comparative psychologists interested in navigation (Chai & Jacobs, 2010; Kelly, 2011; Nardi, Newcombe, & Shipley, 2011, 2012; Nardi, Nitsch, & Bingman, 2010; Restat, Steck, Mochnatzki, & Mallot, 2004). Sloped terrain provides salient and multimodal spatial cues that are unlikely to change quickly over time, and that often, though not always, provide precise directional information. A navigator can use the slope gradient to travel uphill or downhill, left or right (e.g., by keeping the uphill side on the right), and can maintain this heading for as long as the slope stays constant. Various species have been shown to spontaneously reorient using slope (e.g., rats—Miniaci, Scotto, & Bures, 1999; pigeons—Nardi et al., 2010; and humans—Nardi et al., 2011) and to prefer slope information to featural cues (Chai & Jacobs, 2010; Nardi et al., 2012). Pigeons prefer to use slope over two-dimensional features, even when this information is conflicting

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(Nardi et al., 2010), suggesting that slope is more reliable than features for locating a goal.

Humans, too, are able to use slope information for reorientation in an otherwise ambiguous environment (Nardi et al., 2011) and to align their reference frame of an array of objects to the axis of the slope (Kelly, 2011). Nardi et al. (2011) demonstrated that the vertical axis of slope is privileged in spatial memory, leading to fewer errors that confuse downhill with uphill than errors that confuse left with right. Restat et al. (2004) assessed the role of slope in a large-scale navigational context. The participants in their study learned a regularly laid-out environment on a terrain that was either sloped or totally flat. Participants who learned the layouts of buildings on the sloped terrain performed more accurately on tasks assessing their spatial knowledge of the environment than did participants who learned the buildings on the flat terrain, using various dependent variables, including a judgment of relative direction (JRD) task, sketch maps, and a return-path task.

Although these studies have demonstrated that slope cues can be used effectively, the studies are limited, insofar as the first two are relatively small-scale, and the latter one did not determine whether the large-scale directional slope improved spatial representations for participants in that condition by establishing a preferred frame of reference (e.g., one aligned with the vertical axis of slope) or simply by providing additional spatial information. We devised Experiment 1 to replicate and extend these findings: Does directional slope confer an advantage in large-scale environments when a path and slope are aligned in the preferred orientation (i.e., facing up- or downhill)?

Experiment 1: Simple environments

We created two identical virtual environments (VEs) that differed only on whether the terrain was completely flat, or directionally sloped. Additionally, we wanted to test whether slope established a preferred reference direction, facilitating better performance. Thus, the path through the environment either led directly uphill or downhill, or across the slope (i.e., orthogonal to the vertical axis of the slope). We hypothesized that Experiment 1 would replicate findings that slope makes it easier for participants to learn the locations of buildings than does a flat environment. However, we also were able to analyze whether slope led to improved performance because it provided a salient reference orientation, or because it added spatial information that could be incorporated into a representation (e.g., verbal—"that building is uphill from me," or spatial—buildings coded with their relative elevations). By testing participants with imagined headings that were either facing across the slope or aligned with the slope, we were able to examine which representation emerged. Because previous research indicated that participants align their frame of reference with slope in a small-scale space (Kelly, 2011), and make fewer across-the-slope errors than slope-based errors in reorienting (Nardi et al., 2011), we assumed that the uphill-downhill axis would establish the reference frame, not the orthogonal axis. If the vertical axis of slope was the preferred reference direction, performance for an off-site pointing task (i.e., one in which no environmental cues were available during the task) should be facilitated when facing that direction, and impaired when facing across the slope. If the directionality of slope was useful because it provided additional spatial information facilitating learning the locations of buildings but not establishing a strong organizing reference frame, the slope condition should have an advantage, regardless of the facing direction.

Method

Participants

A group of 45 participants (26 female, 19 male) were recruited from the undergraduate population of a large urban university and participated in exchange for class credit. Participants had an average age of 20.76 years (*SD* = 2.96). The sample consisted of 27 Caucasian, seven African-American, and six Asian participants. The remaining five participants reported their ethnicity as either Hispanic, Indian, or "Other." We cut off data collection at the end of an academic semester, with the approximate aim of collecting 50 participants.

Materials

The experiment was administered on a desktop Alienware computer running Windows 7 64-bit with an Intel Core i7 960 3.20-GHz processor and NVidia GeForce GTX 460 graphics card. The VE was created using Unity 3D (free version; www.unity3d.com) and populated with buildings using Google Sketchup (http://sketchup.google.com). The experiment was conducted and displayed on a 32 × 52 cm monitor. Participants moved around the environment using a mouse and arrow keys on a keyboard. The reconstruction task was administered in Adobe Illustrator.

Self-report and spatial measures

These measures were administered via pencil and paper.

Santa Barbara Sense of Direction Scale (SBSOD; Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) The SBSOD consists of 15 items that participants respond to on a 7-point Likert scale. The scale is designed to measure whether participants thought they were good or bad navigators, with lower scores indicating worse navigation ability.

Spatial orientation test (SOT; Kozhevnikov & Hegarty, 2001; we used the revised version by Hegarty & Waller, 2004) The SOT 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. In all, 5 min are allowed to complete the 12-item measure. The angle between the correct answer and a participant's response is recorded for each item, and these errors are averaged to yield an overall error score. If participants did not complete all 12 items, a value of 90º was assigned to each uncompleted item, adjusting the error score as if the answer was a random guess.

Video game questionnaire (VGQ; Green & Bavelier, 2007) The VGQ is a questionnaire that measures experience with video games. The VGQ assesses frequency of use, length of use, and which types of video games are played the most. Responses were coded by the total number of hours played per week over the past year, for all types of games and for just action games.

Virtual environments

Two VEs were created using Unity 3D. The VEs each consisted of 11 buildings along a route. Five of these buildings were marked with blue gems and had signs that gave their names (see the left panel of Fig. 1 for the configuration of the relevant buildings). A path through the environment, from which participants could not stray, had three right-angle turns. The layouts of buildings, paths, signs, and so forth, were placed in identical spatial locations in both environments. However, one virtual environment had terrain that was completely flat, whereas the other was placed on homogeneous (at an approximately constant incline) directionally sloped terrain. The slope was kept as close to 15º as possible, but was flattened at the locations off the routes where buildings were placed to make them appear more realistic. A slope of 15º, although very steep in the real world, was chosen to make the slope as salient as possible while still being possible to walk on. The slope was aligned with the route, so that participants traveled either parallel or orthogonally to the direction of the slope. Two of the five path segments proceeded directly uphill or downhill, whereas three of the five paths led orthogonally across the hill. To further increase the saliency of slope information, the rate of walking was modulated, so that participants traveled more slowly uphill and more quickly downhill. The walking speed on the flat surface was the default speed for Unity 3D. A curve was created that adjusted walking rate according to the slope of the terrain, to continuously increase the walking speed downhill (maximum of 40 %) and decrease the walking speed by the same percentage uphill.

A separate VE was constructed for the VE pointing task. The environment only consisted of a flat ground plane and a sky, with a crosshair in the center of the screen and a number indicating the degrees in the upper left that changed as the crosshair was rotated (see Fig. 2). Participants were placed in the center of a circle, inside of which were eight spokes. At the 0º, 90º, 180º, and 270º positions, the letters "F," "R," "B," and "L" appeared, respectively. Participants then stood stationary at the center of the compass and could rotate around, using the mouse to view all 360º. The experimenter informed participants that the letters indicated the "front," "right," "back," and "left." "Front" would indicate facing direction, and the other letters served as reference points as participants rotated.

Procedure

Participants first provided informed consent, then completed the three paper-and-pencil measures. To ensure that conditions were equated for navigation ability, participants were randomly assigned a condition on the basis of whether they scored above or below a previously obtained average of the SBSOD (65, out of a possible range of 15–105). This cutoff was determined a priori. Participants first completed the SBSOD, which was quickly scored by the experimenter while the remaining two measures were completed. The experimenter then assigned each participant to a condition (flat or sloped) and a route direction (whether the participant started the route at one endpoint and proceeded to the other, or vice versa). Participants were randomized by gender and by SBSOD score (above or below the median).[1]

VE learning phase

After the paper-and-pencil measures were completed, participants began the VE learning phase. Participants sat at a desk in front of a computer monitor while the experimenter explained the controls. The experimenter demonstrated that moving the mouse changed the view in the environment whereas pressing the arrow keys allowed movement backward, forward, and laterally. The experimenter also demonstrated how the mouse and arrow keys could be used together to travel forward while turning. Participants then had as much time as needed to familiarize themselves with the controls. When participants indicated that they felt comfortable, they were instructed to travel back to the start.

The experimenter then explained that in the VE, participants would encounter five buildings and that the names and locations of these buildings were crucial for the tasks that followed. A blue gem floating just above head level marked a building that participants would have to remember, and a

[1] Participants were never informed of their score on the SBSOD or on any other measure.

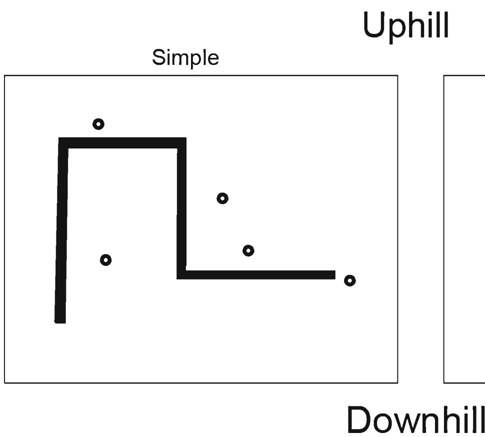

Fig. 1 Schematized aerial views: Simple and complex environments. The layouts of the simple environments from Experiment 1 (left) and the complex environments from Experiment 2 (right) are viewed from above. The buildings (indicated as black dots with white centers) were marked with blue gems in the actual environment. Participants traveled along the path and were instructed to travel from the beginning, all the way to the end, and back to the beginning. The participants were constrained by invisible walls, preventing them from freely exploring the rest of the environments. The directions in which the environment was learned were counterbalanced between participants. Direction 1 for the simple environment began at the right and ended at the bottom left; for the complex environment, Direction 1 began at the top and ended at the bottom. Direction 2 was the exact reverse of Direction 1

sign next to the building provided its name (see Fig. 3). Participants were told to remember the name of each building and its location relative to all of the other buildings they learned. Before the learning phase began, the experimenter explained that participants would complete two tasks: a pointing judgment task and a reconstruction task. Participants had as much time as they needed to navigate the environment, but they were asked to go through the environment once forward and once backward and to notify the experimenter when they had finished.

VE spatial memory tasks

VE pointing task In the VE pointing task (called elsewhere "judgments of relative direction," or JRDs), participants were placed in the blank VE. The experimenter gave participants an instruction sheet that explained the details of the task. The experimenter told them to read over the instructions and to let the experimenter know if they had any questions. In the instructions, participants were told to imagine that they were standing directly underneath the blue gem at one of the

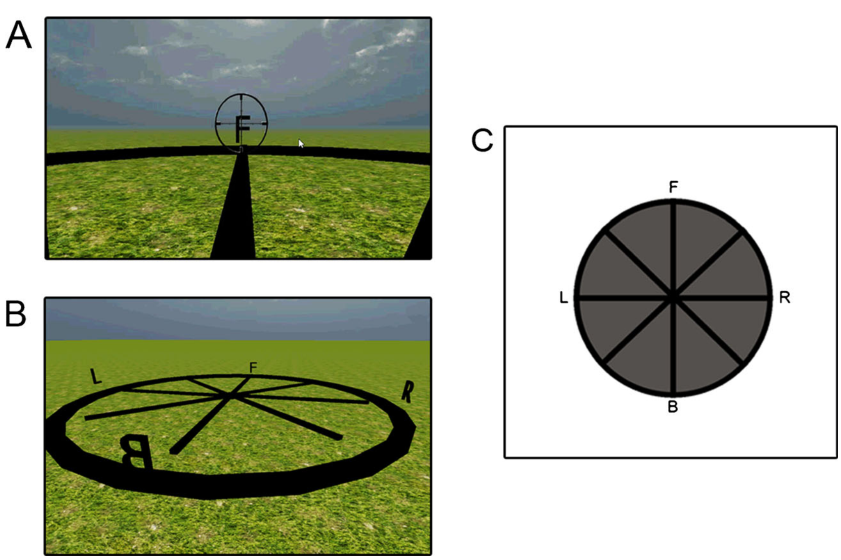

Fig. 2 Compass from the virtual-environment (VE) pointing task: Participant view (A), screenshot of actual compass (B; not seen by participants), and schematized aerial view of the compass (C). Participants stood in the center of the circle and could rotate freely around 360º. They were instructed that the "F" indicated the direction that they were facing, the "R" indicated 90º to the right, "L" 90º to the left, and "B" behind. The spokes in the center of the compass provided reference information as the participant rotated, but at least one letter was visible on the screen at all times

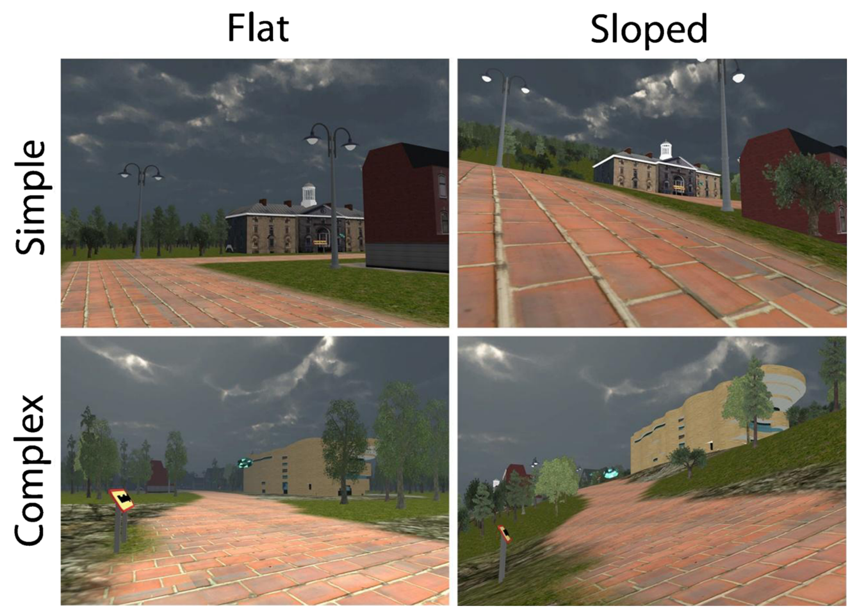

Fig. 3 Participant views of the virtual environments: Point-of-view screenshots from the simple environments (top two images) and complex environments (bottom two images), in both the flat (left two images) and sloped (right two images) conditions. The blue gems (one is visible in the center of the complex-environment images) indicated buildings to be learned by the participant. The names of the buildings were clearly displayed on signs along the path. Participants were constrained to move along the path by invisible walls that prevented them from moving elsewhere in the environment. Note that the path in the complex-sloped environment was curved, nonhomogeneous, and misaligned with the vertical axis of the slope. The slope in the simple-sloped environment, on the other hand, was straight, homogeneous, and aligned with the vertical axis

buildings and, when the crosshair was pointed at "F" on the compass, they were facing down the route in the direction of the next building (i.e., facing the direction that the route went, not necessarily facing directly toward the next building). Participants were shown a schematic depiction to demonstrate this. Their task was to point the crosshair at the other buildings they had learned and to record the number on the screen. The task had no time limit. The first building was used as an example. The experimenter explained by saying "You are standing underneath the gem at Building X. When the crosshair points at the F, you are facing down the route toward Building Y. Now, you rotate the crosshair around to indicate how you would point to Building Z." Participants then pointed the crosshair at Building Z. If a participant did not respond correctly, the experimenter explained the task again and demonstrated the correct answer. Excluding the last building, participants pointed from each building to all of the other buildings in the environment, for a total of 20 pointing judgments (five imagined locations, pointing to the other four buildings from each location). The error, corrected for being greater than 180º, of these 20 judgments was averaged to yield error scores for the individual participants.

Reconstruction task In the reconstruction task, the experimenter presented participants with a blank Adobe Illustrator document with five icons that they were told represented the five buildings in the environment. The icons were red circles with a white dot in the middle of each, and were initially presented at the bottom of the screen. The icons were presented in the order in which that participant had learned the buildings in the environment, from left to right. The experimenter asked participants to move the five icons around the screen and to place them where the participant thought they would best represent a map of the environment from an aerial view. Participants were informed that they could place the icons in any orientation that they wanted, so long as the overall configuration was, to the best of their ability, accurate. Participants were given as much time as they needed for the reconstruction task. The data analysis of the reconstruction task was controlled for translation, orientation, and scaling using a bidimensional regression (Friedman & Kohler, 2003; Tobler, 1994).

Follow-up measures After participants completed the reconstruction task, they completed a task to measure their memory for the buildings. The experimenter presented participants with screenshots of the five buildings, taken from underneath the blue gems facing the buildings, and asked the participant to write down what building they thought each was. The order of presentation of the pictures was randomized. After completing the memory task, the experimenter presented the participants with a final questionnaire. The questionnaire served as a check that participants had noticed and used the slope in the relevant condition. The questionnaire consisted of Likert-scale questions about the participants' strategies when learning the environment and completing the tasks. Participants rated how true six statements were (1 = *not true at all*, 7 = *very true*). The questions that the participants were asked were as follows: (1) whether they noticed the slope; (2) whether they had used the slope; (3) whether they had used other objects in the environment (i.e., trees, streetlights, and other buildings); (4) whether they had visualized the environment from an aerial view; (5) whether they forgot the locations of any of the buildings; and (6) whether they forgot the names of any of the buildings. After the follow-up questions, the participant was debriefed.

Results

No gender differences were observed on any of the tasks. Thus, the following analyses are collapsed across this variable.

VE pointing task

The angle between the correct pointing judgment and the participant's response was measured for each trial and subtracted from 360 if it was greater than 180, yielding the absolute error for each trial. Pointing judgments were considered to be aligned with the slope if participants imagined facing directly uphill or downhill. Two averages were calculated for each participant: trials on which the orientation was aligned with the slope (facing uphill or downhill), and trials on which the orientation was not aligned with the slope (facing across the slope). Because we counterbalanced the directions in which the route was first experienced, eight facing orientations were possible, four of which were aligned and four of which were misaligned. We ran a 2 (condition) × 2 (alignment) × 2 (high or low SBSOD) mixed-factors analysis of variance (ANOVA). Recall that we hypothesized a main effect of condition, with slope conferring an advantage as compared to the flat environment. The analysis revealed a main effect of condition, $F(1, 41) = 4.82$, $p = .03$, $d = 0.69$, such that participants in the slope environment pointed with less error ($M = 31.88$, $SD = 4.70$) than did participants in the flat environment ($M = 46.28$, $SD = 4.58$). For the effect of alignment, if slope provided a preferred frame of reference that participants used to locate the other buildings, facing uphill or downhill should be more accurate for the slope than for the flat condition. However, we found no main effect of alignment, $F(1, 43) = 3.03$, $p = .09$, $d = 0.53$, and, crucially, no interaction between condition and alignment, $F(1, 41) = 0.38$, $p = .54$, $\eta_p^2 = .01$ (see Fig. 4). In addition, the simple effect of aligned versus misaligned pointing was not significant for the slope condition, $t(22) = 1.06$, $p = .30$, $d = 0.45$, suggesting that the participants performed no better within the slope condition for aligned than for misaligned pointing. We also observed no main effect of SBSOD, $F(1, 41) = 0.11$, $p = .74$, $d = 0.10$, and all of the other interactions were nonsignificant, all ps > .41.

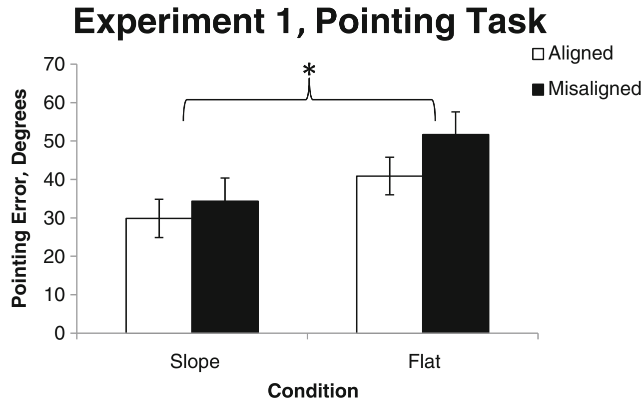

Fig. 4 Performance on the virtual-environment (VE) pointing task of Experiment 1. In Experiment 1, a main effect of condition was found, such that participants in the slope condition pointed more accurately (i.e., had less pointing error) than participants in the flat condition. This was the case whether the pointing judgments were aligned or misaligned with the slope (or the equivalent direction, in the flat environment). Error bars = ±1 *SEM*

Reconstruction task

The reconstruction task was analyzed using a bidimensional regression (Friedman & Kohler, 2003). The bidimensional regression (r^2) controlled for the translation, orientation, and scale of the participant's representation of the environment. The reconstruction task in Experiment 1 exhibited a ceiling effect and a large amount of skew (skew = −1.49). We therefore conducted a Mann–Whitney U test between the rank scores for condition (sloped or flat). A significant difference between conditions emerged, with the slope condition eliciting significantly better performance than the flat condition, Mann–Whitney $U = 163$, $Z = 2.04$, $p = .04$ (see Fig. 5). We found no effect of SBSOD group on reconstruction performance overall, $U = 214$, $Z = 0.89$, $p = .38$, and the effects of condition were similar for the high-SBSOD and low-SBSOD groups (i.e., no interaction). The reconstruction task was highly and significantly correlated with pointing error, $r(44) = −.58$, $p < .001$.

We were also interested in how participants spontaneously oriented their reconstructions. Because the instructions were to arrange the buildings around the map in any orientation that the participant wanted, we could analyze the theta values from the bidimensional regression to determine which orientation the participant chose. Theta is the angle at which the configuration of the participants' points can be optimally rotated to bring them into accord with the actual configuration of the points. This angle does not affect the overall r^2, but instead provides insight regarding the orientation of participants' representations. We expected that the thetas for both conditions would indicate bias toward the starting direction, since that is a strong organizer of cognitive representations in the absence of other cues. However, if the direction of the slope contributed to (or competed with) the starting direction, we would expect to see maps oriented differently (aligned with the vertical axis

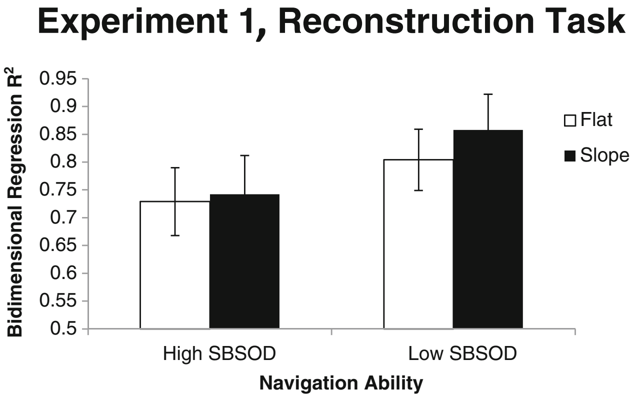

Fig. 5 Performance on the reconstruction task of Experiment 1. In Experiment 1, we found a main effect of condition on the reconstruction task. SBSOD = Santa Barbara Sense of Direction Scale. Error bars = ±1 *SEM*.

Table 1 Experiment 1 correlations between spatial measures and virtual-environment spatial memory tasks

Variable	SBSOD	SOT	Pointing Error	Model Building	Mean	*SD*
SBSOD	–				63.80	15.09
SOT	.01	–			51.09	26.01
Pointing error	.06	.55**	–		39.40	22.78
Model building	–.09	–.30*	–.58**	–	.77	.24

Pointing error and the SOT are scored as the amounts of error (i.e., the higher the error, the worse performance), so the negative correlations between them and other measures indicate improved performance. SBSOD, Santa Barbara Sense of Direction. SOT, spatial orientation test. *SD*, standard deviation. * $p < .05$. ** $p < .01$

of the slope) in the slope condition, as compared to the flat condition. When participants' starting direction was facing orthogonally to the vertical axis of slope, only two participants in the slope condition oriented their maps with the slope at the bottom; eight placed their starting location at the bottom. For the same starting direction in the flat environment, all participants aligned their maps with the starting location at the bottom of the map. When the starting orientation and direction of the slope were the same direction, all but two participants in the slope condition oriented their maps with the starting location at the bottom (and aligned with the slope). In the same direction for the flat condition, six participants oriented their maps with starting location at the bottom, but five rotated the map 90º, possibly orienting their map with the longest path segment (Mou, McNamara, & Zhang, 2013). On the basis of this assessment, participants overall used their starting location to establish a spatial reference frame, regardless of slope. These data corroborate the finding from the VE pointing task that slope did not appear to affect the reference frame used to organize participants' representations.

Self-report and spatial measures

The SBSOD was uncorrelated with either spatial memory task, rs < |.09|, ps > .56. The SOT predicted performance on both the reconstruction task, $r(44) = -.30$, $p < .05$, and the VE pointing task, $r(44) = .55$, $p < .001$. The SOT and SBSOD were not correlated with each other, $r(44) = .01$, $p = .94$ (see Table 1). As measured by the VGQ, gamers and nongamers were not significantly different on either navigation task.

Follow-up measures

Participants in the slope condition self-reported noticing the slope significantly more than did participants in the flat condition, $t(43) = 9.67$, $p < .001$, $d = 2.95$, and self-reported using the slope more than did participants in the flat condition, $t(43) = 2.44$, $p = .02$, $d = 0.74$. None of the other self-report items from the follow-up test were different between the two conditions, all ps > .19. Neither of the slope-related items correlated with performance on either the VE pointing task or the reconstruction task. Participants also did not differ on the building memory task.

Discussion

Experiment 1 replicated the finding of Restat et al. (2004): Performance was consistently more accurate in the slope condition than in the flat condition, as measured by the reconstruction and VE pointing tasks. On the basis of a more detailed analysis of the pointing task, however, this effect was not driven by trials that required participants to imagine an orientation that was aligned with the more salient axis of the slope (i.e., vertical; Nardi et al., 2011). Rather, the sloped terrain conferred an overall advantage during pointing. This finding suggests that the directional slope could be recalled and used to generate more accurate pointing, even in cases in which the frame of reference was not aligned with imagined heading. Interestingly, the measure of navigation ability, SBSOD, did not correlate with either navigation task. This suggests that taking advantage of a highly salient, simple directional cue in an environment does not depend on navigational ability per se. The SOT, on the other hand, was correlated with both VE spatial memory tasks. In factor analyses, the SOT has been shown to load with other measures of perspective-taking ability (Hegarty & Waller, 2004), suggesting that participants' ability to imagine a heading in the environment was a factor correlating with success on the VE spatial memory tasks, even if broader navigational ability (SBSOD) was not.

Consistent with the previous literature, we found that participants were able to use the spatial information provided by a directional slope, at least when the relations between slope and path were simple. We also showed that slope provides additional spatial information, but not by creating a preferred reference orientation. Rather, participants in the slope condition made accurate pointing judgments when facing either parallel or orthogonal to the direction of slope. Reconstructions of the VE, though more accurate overall in the slope condition, did not show different patterns of orientation in the two conditions.

However, in Experiment 1, as in all of the studies so far, the environments used to study slope have kept the relation between path and slope relatively simple. Would this effect hold for environments that were more like the local-park example than San Francisco? To investigate this, we used the same methodology, but increased the complexity of the relation between the slope of the environment and the path through it.

Experiment 2: Complex environments

In Experiment 1, the paths through the environment were straight and aligned with the slope. Moreover, in Experiment 1 and the other studies on slope, the environments' terrain has always been homogeneously sloped, meaning that the slope rises at a constant angle. Varying these environmental properties increases the complexity of the relations between the path and the slope, making the directional information provided by the slope more difficult to use to provide additional spatial information. It is unclear whether the effects of sloped terrain would emerge in cases in which the relations between path and slope were more complex. The same spatial cue is available—that is, locations around the environment can be represented in terms of uphill or downhill from each other. However, this information is more difficult to integrate into a spatial representation, as compared to a simple environment with a homogeneous sloped terrain. We speculated that whether or not participants would use the slope information would depend on the strategy that they employed to learn the environment.

Many studies have shown individual differences in navigation ability (e.g., Hegarty et al., 2002), including the finding that individuals of varying ability use different strategies (i.e., verbal, procedural, or spatial) to encode locations in a space (e.g., Baumann, Chan, & Mattingley, 2010; Wen, Ishikawa, & Sato, 2011). When the relation between path and slope is simple, slope provides an easy way to bolster either representation, because it can be encoded relatively simply, either verbally or spatially. Increasing the complexity of the relations between path and slope may, then, have differential effects on navigators with different strategies. We hypothesized that poor navigators would not be able to effectively incorporate the more complex spatial information into a symbolic verbal representation, and thus would show no benefit in the sloped environment. Good navigators, on the other hand, might use the directional slope information to augment their spatial representations (e.g., by maintaining a constant heading of uphill as they navigate that would allow them to calibrate errors along a curved path).

The data from Experiment 1 suggested that slope provides additional spatial information, but does not necessarily provide a preferred reference frame to which participants referred during the pointing and reconstruction tasks. We devised Experiment 2 to determine whether slope provided an advantage to participants in a case more like a local park than like San Francisco streets—that is, in which the relations between directional slope and the path that a navigator follows change continuously. We were also concerned about the lack of correlation between the SBSOD and the VE spatial memory tasks in Experiment 1. The strong correlation between SOT and the VE spatial memory tasks meant that the navigation tasks were spatial tasks, but they may not have measured navigational behavior per se. In Experiment 2, we made the relation between the path and the directional slope more complex in several ways, to require participants to use navigationally relevant skills and shift participants away from a verbal or categorical encoding strategy. All of the following changes decreased the likelihood that participants would be able to use a verbal encoding strategy to incorporate the slope into their representation.

We changed three properties of the VE to increase the complexity of the slope–path relation. First, we misaligned the slope with the path, because we wanted to ensure that the path and slope were not creating reinforcing reference frames. Second, we curved the path, because studies have shown that increasing the path curvature increases heading bias toward the direction of the curve and can lead to less efficient path integration (Kelly, Beall, Loomis, Smith, & Macuga, 2006; Lappe, Stiels, Frenz, & Loomis, 2011), meaning that participants who relied on the path would be more error prone than participants relying on the slope. Curving the path was also important so that participants could not use a verbal code to mark each turn, but instead would have to rely on path integration to determine the interrelationships of the buildings in the flat as well as the sloped environment. Third, we decreased the homogeneity of the slope, to require participants to actively maintain the direction of slope in that condition. We also increased the number of buildings that participants had to learn from five to seven.

Would all participants still be able to use the slope information effectively? If directional slope provides additional spatial information that is easy and efficient to incorporate into a representation, the main effects from Restat et al. (2004) and Experiment 1 should be replicated. If, however, slope provides an advantage only for participants who are able to incorporate the additional spatial information into their representations, only good navigators should be able to use the directional slope information effectively.

Method

Participants

A group of 52 participants (26 female, 26 male) were recruited from the undergraduate population of a large urban university and participated in exchange for class credit. We collected participants with the approximate aim of 50, but cut off our data collection at the end of an academic semester after balancing for gender.

Materials

The materials were identical to those of Experiment 1, with the exceptions that the VEs were different and that the water-level test was administered instead of the SOT (this was due to an experimental error).

Self-report and spatial measures

These measures were administered via pencil and paper.

Water-level test (WLT; Piaget & Inhelder, 1948/1956) The water-level test consists of six bottles, tilted in different orientations. Participants are required to draw the line indicating how water would look sitting in the bottle, presuming that the ground is at the bottom of the page. The angular deviation off from horizontal is measured. Participants are assigned 2 points for answers deviating less than 5º, 1 point for answers between 5º and 10º, and 0 points for answers deviating more than 10º. The possible range is therefore 0–12.

Virtual environments Two virtual environments were created using Unity 3D. These environments consisted of 12 buildings, seven of which were required to be learned. The route through the environment consisted of one major turn that was not at a right angle. The route was also designed not to be in alignment with the major axis of the slope. The degree of the slope varied between 0º and 15º, but it was always oriented in the same direction. The buildings used were the same as in Experiment 1, but their locations were altered to suit the more complex terrain.

The same VE was used for the VE pointing task.

Procedure

Participants first provided informed consent, and then completed the three paper-and-pencil measures. Participants were not randomized on SBSOD score, but were instead randomly assigned to a condition (sloped or flat) and direction. Follow-up analyses showed that the two groups were not significantly different on SBSOD score. The procedure was identical to that of Experiment 1, with the exception that no follow-up questions were administered.

Virtual environment The VE learning and testing procedures were identical to those of Experiment 1.

Results

VE pointing task

We ran a 2 × 2 between-subjects ANOVA with Condition (sloped or flat) and SBSOD (high and low) as factors. Neither the main effect of condition, $F(1, 48) = 0.03$, $p = .87$, $d = 0.06$, nor the interaction between SBSOD and condition, $F(1, 48) = 0.91$, $p = .34$, $d = 0.48$, was significant. The main effect of SBSOD was marginally significant, $F(1, 48) = 3.30$, $p = .08$, $\eta_p^2 = .02$. The low-SBSOD group had (numerically, but not significantly) higher errors ($M = 53.89$, $SD = 16.63$) than the high-SBSOD group ($M = 45.86$, $SD = 16.77$). See Fig. 6. Note that no patterns differentiated the high- and low-SBSOD participants in the flat or the sloped condition on the basis of the imagined heading at different locations around the environment (nor were we expecting them, since all imagined headings were oblique with respect to the slope).

Reconstruction task

We ran a 2 × 2 between-subjects ANOVA on the bidimensional regression coefficients (r^2), with Condition (sloped or flat) and SBSOD (high and low) as factors. We observed no main effect of condition, $F(1, 48) = .004$, $p = .95$, $d = 0.08$, and no main effect of SBSOD, $F(1, 48) = 2.37$, $p = .13$, $d = 0.34$. We did find a significant interaction between condition and SBSOD, however, $F(1, 48) = 6.45$, $p = .01$, $\eta_p^2 = .12$. Follow-up contrasts, corrected for multiple comparisons using Tukey's HSD, revealed that the interaction was driven by the high-SBSOD group performing significantly better in the slope condition than the low-SBSOD group, $t(21) = 2.72$, $p < .05$, $d = 0.87$. That is, good navigators were able to use the slope cues during the reconstruction task to perform better in the slope than in the flat condition (indeed, the low-SBSOD group was numerically worse in the slope than in the flat condition, but this difference was not significant). Correcting for multiple comparisons, the other pairwise contrasts (high vs. low SBSOD within the flat condition; low-SBSOD group in the flat vs. the sloped condition) were not significant, all ps > .29 (see Fig. 7). The VE spatial memory measures were highly and significantly correlated with each other, $r(51) = -.46$, $p = .001$.

Self-report and spatial measures

Overall, the only significant correlation between a spatial skill measure and a VE spatial memory task was between the VE

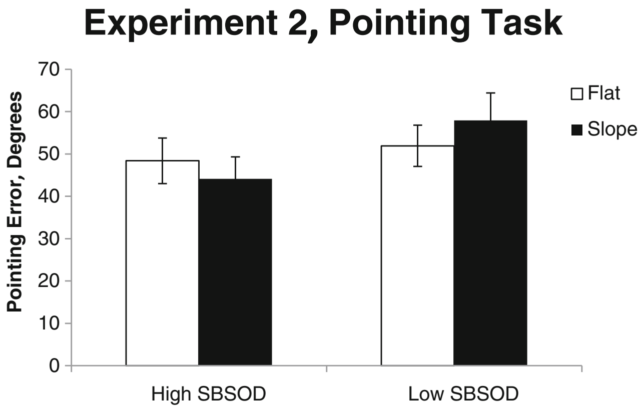

Fig. 6 Performance on the virtual-environment (VE) pointing task of Experiment 2. In the complex environments, we observed no main effects of condition or SBSOD, nor an interaction. SBSOD = Santa Barbara Sense of Direction Scale. Error bars = ±1 *SEM*

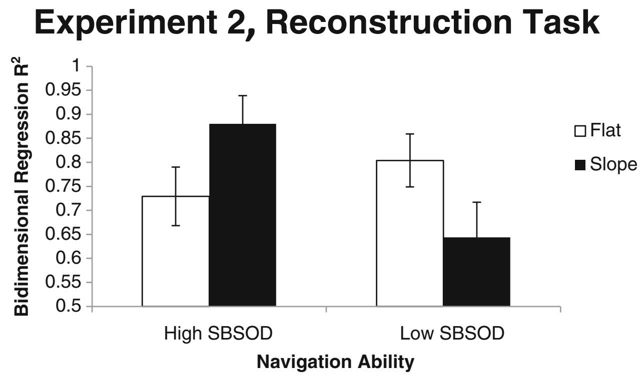

Fig. 7 Performance on the reconstruction task of Experiment 2. The reconstruction exhibited a significant interaction between condition and navigation ability. The interaction between condition (flat vs. sloped environment) and navigation ability (high and low) is depicted. Participants scoring above the median on the SBSOD performed better on the reconstruction task in the sloped than in the flat environment. No other follow-up contrasts were significant. SBSOD = Sant Barbara Sense of Direction Scale. Error bars = ±1 *SEM*

pointing task and the SBSOD, $r(51) = -.38$, $p < .01$. The SBSOD was also marginally correlated with the reconstruction task, $r(51) = .27$, $p = .06$. A correlation analysis corroborated the interactions between SBSOD and the navigation measures in the ANOVAs presented in the preceding sections. The patterns of correlation were different for the sloped than for the flat condition. In the slope condition, both the VE pointing task, $r(22) = -.56$, $p < .01$, and the reconstruction task, $r(22) = .52$, $p = .01$, were significantly correlated with SBSOD. This was not the case in the flat condition for either the VE pointing task, $r(28) = -.18$, $p = .34$, or the reconstruction task, $r(28) = -.07$, $p = .73$ (see Table 2 and Fig. 8). No correlations or differences resulted between video game play, measured by the VGQ, and performance on the VE spatial memory tasks.

Comparison between Experiments 1 and 2

Overall, the VE pointing task in the complex environment ($M = 49.88$, $SD = 16.98$) was significantly more difficult than the VE pointing task in the simple environment ($M = 39.40$, $SD = 22.78$), $t(95) = 2.59$, $p = .01$, $d = 0.52$. The reconstruction task, on the other hand, was equally difficult in both experiments, $t(95) = 0.22$, $p = .82$, $d = 0.05$. The patterns of correlations between the SBSOD and the VE spatial memory tasks were different between Experiments 1 and 2. In Experiment 1, SBSOD was not correlated with either navigation task, regardless of condition.[2] In Experiment 2, however, the VE pointing task was significantly correlated with SBSOD, and the reconstruction task was marginally correlated with SBSOD. Figure 8 displays the correlations between SBSOD and both VE spatial memory tasks from Experiments 1 and 2. The lack of correlation between SBSOD and the tasks in Experiment 1 is shown in the scatterplots on the left side of the figure. The correlations between SBSOD and the tasks in Experiment 2 are shown on the right side. Note that, for both tasks in Experiment 2, the linear relationship is steeper for participants in the slope than in the flat condition. Thus, despite the lack of a significant interaction on the pointing task when analyzed with a median split (a common statistical technique employed in individual-difference studies in navigation; e.g., Epstein, Higgins, & Thompson-Schill, 2005; Wen et al., 2011), the scatterplots suggest that good navigators were able to take advantage of the slope cues in that condition.

[2] Dividing the correlations by condition for Experiment 1 yielded no significant linear relationships between SBSOD and either VE spatial memory task, all ps > .10.

Discussion

In Experiment 2, when the relation between path and slope was more complex, we found that using slope to more accurately represent an environment varied with navigation ability, unlike in Experiment 1 and in much of the previous research. The main effect of slope was only significant for the high-SBSOD group on the model-building task. Because we made the relations between path and slope more complex than in Experiment 1, the slope could not be as easily represented with a categorical coding strategy, and the directional information provided by slope could only be incorporated by navigators who encoded the environment using a spatial strategy (i.e., good navigators).

Participant performance on the pointing task was less accurate in the complex environments than in the simple environments for both the slope and flat conditions. The curved path and two additional buildings made the task more difficult overall, not more difficult specifically due to the increased spatial complexity caused by the slope. This increased difficulty made the complex environments more navigationally demanding, as was shown by the correlation between the VE

Table 2 Experiment 2 correlations between spatial measures and virtual-environment spatial memory tasks

Variable	SBSOD	WLT	Pointing Error	Model Building	Mean	*SD*
SBSOD	–				66.31	14.50
WLT	.20	–			6.38	3.44
Pointing error	–.38**	–.24†	–		49.88	16.98
Model building	.27†	.16	–.46**	–	.78	.21

Pointing error is scored as the amount of error (i.e., the higher the error, the worse performance), so the negative correlations between that and other measures indicate improved performance. SBSOD, Santa Barbara Sense of Direction. WLT, water-level test. *SD*, standard deviation. † $p < .10$. ** $p < .01$

spatial memory tasks and SBSOD. Importantly, increasing the complexity did not impair bad navigators in the slope condition relative to the flat condition. Despite this increased difficulty, good navigators were able to take advantage of the information provided by the slope to perform significantly better than the bad navigators in the slope condition, as revealed by the difference in performance on the model reconstruction task. The correlations between SBSOD and performance on both VE spatial memory tasks corroborated the relationship between navigational ability and performance in the complex, but not the simple, environments.

General discussion

We devised two experiments to elucidate the manner in which directional slope leads to more accurate performance in navigation tasks. Previous work has shown that slope is a highly salient cue that provides additional spatial information that can be used to enhance the accuracy of representations of large-scale (Restat et al., 2004) and small-scale (Kelly, 2011; Nardi et al., 2011) environments. Research on slope cues has revealed mixed results for the question of individual differences. Whereas some studies have shown an overall effect of slope providing additional spatial information or being a

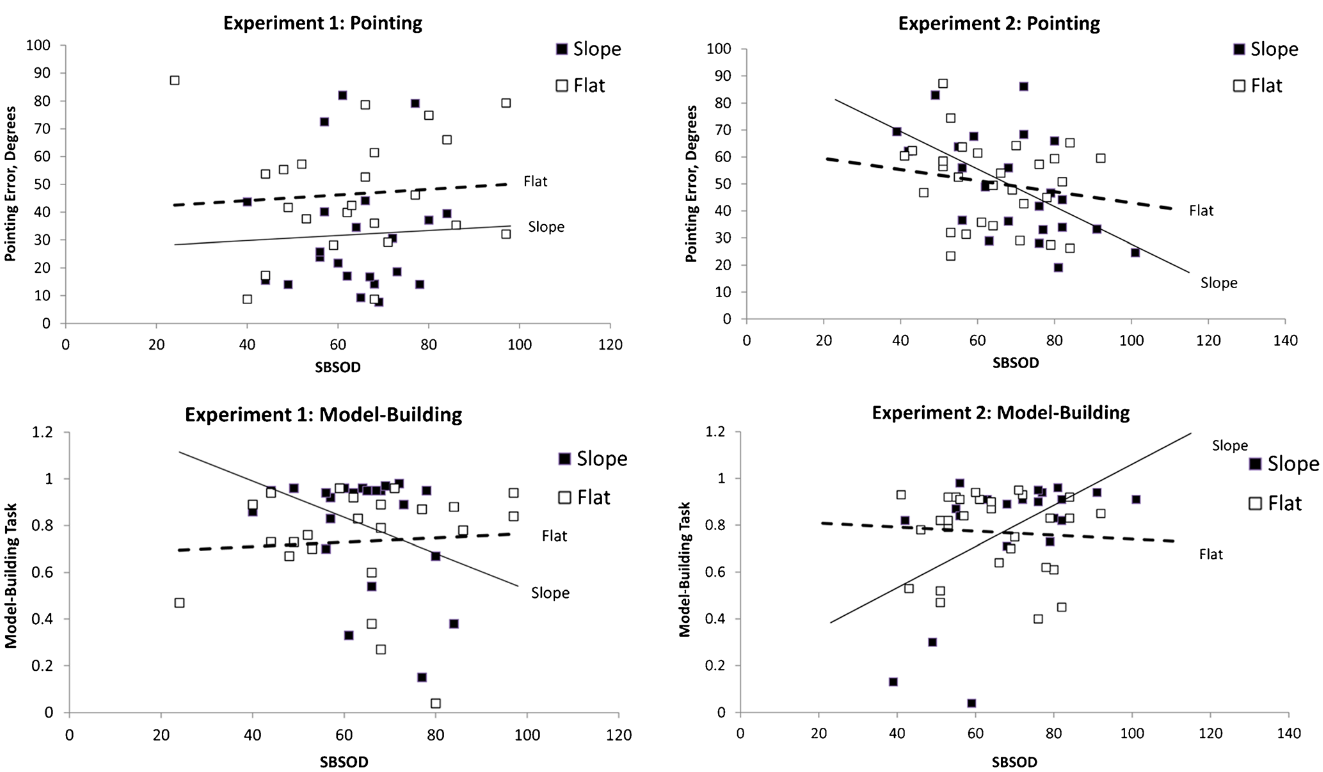

Fig. 8 Scatterplots for virtual-environment (VE) spatial tasks and the Santa Barbara Sense of Direction score (SBSOD). The lack of correlations in Experiment 1 (left panels, top and bottom) between SBSOD and the VE spatial memory tasks occurs for each condition (flat and slope). In Experiment 2 (right panels, top and bottom), however, the SBSOD and the VE spatial memory tasks are significantly correlated for the slope condition (pointing task, $r = -.56$, $p = .005$; reconstruction task, $r = .52$, $p = .01$), but not for the flat condition (pointing task, $r = -.18$, $p = .35$; reconstruction task, $r = -.07$, $p = .72$). This set of scatterplots suggests that navigation ability was important for learning the layout of buildings in Experiment 2, but was largely irrelevant for Experiment 1. Moreover, it shows remarkably similar patterns for the VE spatial memory tasks in Experiment 2, with good navigators outperforming bad navigators on both tasks for the slope condition but not the flat condition

salient and organizing spatial cue (Kelly, 2011; Restat et al., 2004), other studies have shown individual differences in the degrees to which slope is used. However, those studies showed individual differences modulated by gender, not navigation ability (Chai & Jacobs, 2010; Nardi et al., 2011). We expanded this work by investigating whether using slope to learn a large-scale environment depends on navigation ability.

In Experiment 1, we designed a large-scale VE to test whether slope is used to establish a preferred reference orientation or simply provides additional spatial information, independent of orientation. By comparing performance to that in a flat environment, we determined that slope cues conferred an advantage to all navigators, both for headings that were aligned with the vertical axis of slope and headings that were across the slope. In addition, the presence of directional slope did not alter the preferred orientation of a reconstruction task between flat and sloped conditions, but the starting direction in the environment did. In Experiment 2, we were interested in whether directional slope would provide an advantage for participants when the relation between path and slope was more complex. We discovered that good navigators performed better in the sloped than in the flat environment, suggesting that directional slope does not unilaterally enhance spatial representations in large-scale environments. How, then, were participants encoding and using the slope in Experiment 1, if only good navigators could encode and use the slope in Experiment 2?

Individual differences in navigation performance are quite common, for a variety of reasons. One emerging line of evidence has suggested that good and bad navigators use different strategies to learn environments. Good navigators may tend to rely on spatial visualization strategies, as opposed to verbal strategies (Baumann et al., 2010; Wen et al., 2011), in encoding environments. On the basis of these findings, when directional cues can be easily encoded verbally, all navigators should benefit from their presence. When directional cues must be encoded spatially, or when it is more difficult to encode them verbally, those participants who use a nonverbal strategy to learn environments will be better able to use them.

Several changes between Experiments 1 and 2 could have led to individual differences in the use of slope: (1) homogeneous versus nonhomogeneous slopes, (2) a path that was aligned or oblique with the slope, and (3) a straight or a curved path. A homogeneous slope that is aligned with straight paths is easy to encode categorically, since the terms “uphill” and “downhill” may be applied in lieu of “ahead” or “behind,” and could then be used by navigators to adopt either a simplistic spatial or a verbal strategy to encode the slope. However, a nonhomogeneous slope that is misaligned with a curved path renders the directional information provided by slope more difficult to incorporate into a spatial representation, and decreases the ease with which a categorical or symbolic representation can be used to encode the direction of the slope with relation to the path.

In addition, the simple VE provided a salient and always-present cue. In the complex environment, encoding and using the direction of the slope required that participants maintain the direction of slope even when the local environment was temporarily flat. Only participants scoring above the median on the SBSOD were able to maintain the directional information provided by the sloped terrain and use this information to form a more accurate representation. Applied beyond slope cues, directional cues should be more likely to be used if they provide consistent sensory input and require little or no inference or strategy on the part of the participant, since the cue is always available during encoding. Thus, a distal mountain range that is constantly visible should be easier to use than one that is obscured by buildings.

Good navigators could have employed one or both of two possible spatial strategies in the complex environment (Weisberg & Newcombe, 2013): First, a “north-like” direction—a heading—could be established as a global organizing principle for the buildings around the environment. Alternatively, slope could augment the representations of building positions—by, for instance, amplifying the salience of whether a turn was left or right, or through elevation data that could be used to encode the buildings relative to each other (e.g., Building A is at position *X*–*Y* along the route and position *Z* in elevation, and Building B is only slightly lower; thus, their positions along the gradient could be similar). Slope did not appear to provide a global organizing direction for the representation of either the simple or the complex environments (or at least, not one strong enough to overcome the starting direction). Thus, we hypothesized that in simple environments, categorical verbal or spatial encoding is a much more straightforward and less cognitively demanding strategy that all participants can adopt to improve their representations. The complex environments, however, rendered this strategy far more difficult to use. It may be that good navigators used the slope information to augment the spatial representation by incorporating elevation data into the positional information about buildings and by highlighting turns along the route. Whereas this study has been the first to show individual differences in using slope as a directional cue, future work should disentangle the exact nature of how directional slope is used by good navigators when the relation between the slope and path is more complex.

Although previous work with slope cues has often reported male advantages, we did not observe gender differences in either experiment. The study that is most similar to the work presented here (Restat et al., 2004) neither observed gender differences, nor individual differences. The evidence on gender differences in navigation ability suggests that males tend to rely on global directions—for example, north–south—and the overall perspective of the environment, whereas females choose to focus on landmarks and self-referenced, typically route-based directions—for example, left–right turns (Lawton, 2010; Sandstrom, Kaufman, & Huettel, 1998; Saucier et al., 2002; Wolbers & Hegarty, 2010). This strategy difference even manifests itself in distinct brain activation for males (left hippocampus) as compared to females (right prefrontal and parietal) during a navigation task (Grön, Wunderlich, Spitzer, Tomczak, & Riepe, 2000). In cases in which gender differences have emerged in slope studies, the participants were required to use the slope cues as allocentric directional cues (e.g., Nardi et al., 2011, 2012), since disorientation obliterated any possible egocentric cues. Similarly, in Chai and Jacobs's (2010) work, participants were required to use slope information (and directional cues more generally) to establish a global direction. Females, who prefer not to use such strategies, performed worse when they were required to use global directional cues, but better when they could use positional landmarks. Because slope was not used to establish a preferred orientation, it is possible that gender effects did not emerge in the present work because multiple strategies were possible for using the directional slope reliably. Additional data on the relationship between strategy, gender, and navigation ability will be needed to address this question directly.

To summarize, the experiments presented here are the first, to our knowledge, to demonstrate that varying the complexity of a virtual environment influences who is likely to use slope cues to enhance their representation of a large-scale space. We have shown that in a simple environment, all participants construct more accurate representations in a sloped than in a flat environment. We provided evidence that the enhanced representations were not due to the fact that slope provided an organizing reference direction. In a complex environment, however, only good navigators can take advantage of the relevant spatial information to improve their spatial representation. Future work should elucidate the roles of two aspects of the relation between path and slope: whether a directional cue must be constantly available in an environment to be used by poor navigators, and whether a directional cue must be easily encoded categorically.

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