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Navigating without vision: spontaneous use of terrain slant in outdoor place learning

Daniele Nardi^a, Katelyn J. Singer^a, Krista M. Price^a, Samantha E. Carpenter^a, Joseph A. Bryant^a, Mackenzie A. Hatheway^a, Jada N. Johnson^a, Annika K. Pairitz^a, Keldyn L. Young^a, and Nora S. Newcombe^b

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ABSTRACT

The topography of the land provides a suite of spatial information for navigation. In an outdoor field experiment, we examined terrain slant as a nonvisual cue. Without being told which cue to use, blindfolded, sighted participants completed a place-learning task in a flat and a slanted site. Errors were significantly smaller in the slanted site. Furthermore, performance in the slanted – but not flat – site was significantly better than expected if guessing the target's direction. This suggests that proprioceptive/kinesthetic and vestibular cues from the slant were spontaneously used for place-learning, albeit with lower accuracy compared to visual cues. Terrain slope might be an environmental cue that is salient and realistically used by blind and sighted persons.

KEYWORDS

Navigation; nonvisual cues; terrain slant or slope; topography; blind

1. Introduction

Spatial navigation is such a common every-day activity that we pay little attention to how we accomplish it (Giudice, 2018). Specifically, what sort of spatial information tends to guide our behavior as we traverse the environment in search of our destination? Research has focused on visual cues (e.g., visual landmarks or beacons) and how these can be used to form an egocentric (route-based) or allocentric (survey-based; the cognitive map) representation of the environment (Klatzky, 1998; O'Keefe & Nadel, 1978; Siegel & White, 1975; Tolman, 1948; Wen, Ishikawa & Sato, 2013). Little attention has been dedicated to the contribution of other sensory modalities for navigation. However, considering nonvisual spatial cues is important for many reasons. First, the visuocentric emphasis in the literature could give a false impression that navigation is uni-sensory, rather than a more complex, multi-sensory process (Cheng, Shettleworth, Huttenlocher & Rieser, 2007; Giudice, 2018; Hohol, Baran, Krzyzowski & Francikowski, 2017). This is particularly relevant given the widespread approach to studying spatial navigation with virtual

environments presented visually to participants in front of a desktop computer. Imagine you are hiking in the woods and you are trying to reach a bridge. You can already hear the sound of the river, but then your trail bifurcates. You choose the path going to the right. Even though vision might be guiding your locomotion (so you avoid obstacles), if the sound of the water becomes fainter as you walk, you will probably reassess your decision, walk back and take the other path. An even more obvious example is the reliance on wind direction when sailing a boat; the sensation and sound of the wind on the face can assist – and often be the primary guiding cue – in determining our course. Second, considering different sensory cues has theoretical implications for the generalization of spatial learning mechanisms. Do the same principles of spatial learning apply to different encoding modalities? In this context, the view of functional equivalence (Bryant, 1997; Loomis, Klatzky, Avraamides, Lippa & Golledge, 2007) proposes that the representation of the environment is amodal and that, with adequate cues and acquisition time, different encoding modalities support equivalent spatial representations, behavior, and performance (Avraamides, Loomis, Klatzky & Golledge, 2004; Giudice, 2018; Levine, Jankovic & Palij, 1982; Nardi, Twyman, Holden & Clark, 2020; Sturz, Gaskin & Roberts, 2014; Yamamoto & Shelton, 2005). Third, studying nonvisual cues has important practical applications because it can fuel innovation in assistive technology for blind navigation (Loomis, Golledge & Klatzky, 1998; Walker & Lindsay, 2006) and multimodal interfaces for the guidance of spatial behavior and safe mobility for people with and without visual impairments (Jacob, Winstanley, Togher, Roche & Mooney, 2012; Jacobson, 2002).

In fact, the relatively scarce literature on nonvisual-based navigation comes mostly from studies examining assistive technology used by blind and/or blindfolded, sighted participants (for a review see: Giudice, 2018; Giudice & Legge, 2008). For example, based on this literature, it is clear that environmental information provided auditorily by mobility aids, in the form of spatialized sounds or spatial language, can support efficient navigation and acquisition of spatial knowledge (Klatzky, Marston, Giudice, Golledge & Loomis, 2006; Loomis et al., 1998; Loomis, Lippa, Klatzky & Golledge, 2002; Marston, Loomis, Klatzky & Golledge, 2007; Walker & Lindsay, 2006). Participants are also able to complete an auditory equivalent of the Morris water maze (Viaud-Delmon & Warusfel, 2014) and to reorient with stable auditory sources in the environment as individual auditory landmarks or geometric configurations (Nardi, Anzures, Clark & Griffith, 2019; Nardi et al., 2020, 2020).

Studies have also addressed navigation with haptic access to the environment. Indeed, probably the simplest mechanical mobility aid for blind navigation is the long cane, which provides haptic information for wayfinding and obstacle avoidance (Giudice & Legge, 2008; in addition, the tapping sounds produced by the long cane can be used for echolocation: Schenkman &

Jansson, 1986). More complex devices that use different types of sensors and provide haptic output, like vibrotactile compasses (Weisberg, Badgio & Chatterjee, 2018) and tongue display units (Chebat, Schneider, Kupers & Ptito, 2011), can effectively guide navigation too. Furthermore, there is evidence that blindfolded, sighted participants could reorient using different tactile landmarks arranged in a specific geometric configuration (Sturz et al., 2014). Finally, let us not forget about navigation based on symbolic devices like tactile and multimodal maps (Giudice, Guenther, Jensen & Haase, 2020).

The present study focuses on the topography of the land as a natural source of spatial information. The purpose was to assess whether sighted, blindfolded participants could navigate using the slant of the ground, which is commonly found in indoor (e.g., ramps) and outdoor (e.g., hills) environments. A uniformly sloped terrain provides a stable directional cue (Jacobs & Schenk, 2003) that can be used to reorient in the environment, maintain course, and encode a target location (e.g., one could remember that, when facing the uphill direction, a target is 45° to the left). Importantly, this slope-based information is multimodal in nature. A hill can be perceived visually (trees and buildings have smaller angles at the intersection with the terrain on the uphill side compared to the downhill side), but it can also be perceived with vestibular and proprioceptive/kinesthetic sensory information. The angles of the joints are different when facing uphill or downhill; furthermore, walking on an incline requires different energetic cost and movement pattern (e.g., leg lift, step length) when ascending or descending (Sun, Walters, Svensson & Lloyd, 1996). Here we are interested in the nonvisual information provided by terrain slope.

Previous studies have already indicated that floor slant can be used for reorientation and spatial memory tasks. For example, rats (Miniaci, Scotto & Bures, 1999; Moghaddam, Kaminsky, Zahalka & Bures, 1996) and homing pigeons (Nardi, Mauch, Klimas & Bingman, 2012; Nardi, Nitsch & Bingman, 2010) can rely on the slope to encode a target location in an arena – and rats can do this even without using vision. Human studies conducted in small-sized environments have shown that floor slant is sufficient to support reorientation (Holmes, Nardi, Newcombe & Weisberg, 2015; Nardi, Newcombe & Shipley, 2011, 2013) and to provide a reference frame for spatial memory (Kelly, 2011). Notably, while in non-human animal experiments the slope was up to 20° steep (Nardi et al., 2012, 2010), human subjects showed successful place-learning with the much gentler slope of 5° (Nardi et al., 2011, 2013) or even 4° (Nardi et al., 2019). Furthermore, participants learned the task when the visual information was impoverished (Holmes et al., 2015; Nardi et al., 2011, 2013) or even completely absent (Nardi et al., 2019). In Nardi et al. (2019), blindfolded, sighted young adults were able to encode the location of a target in a circular search space, and after disorientation, could replace it back with errors significantly smaller than expected by chance using only the

modest slope of the floor (4° inclination). Remarkably, conflict trials revealed that the slant controlled their behavior over competing auditory cues in the environment. Overall, evidence from sighted participants suggests that terrain slant is a useful – and perhaps salient – environmental cue for spatial navigation. However, all these studies were carried out in small-scale, indoor lab environments. Do these findings generalize to real-world settings?

Using a more ecologically valid approach, in this project we tested slope-guided navigation in an outdoor field experiment. Blindfolded, sighted, young adult participants completed a place-learning task on a college campus lawn (Figure 1). We employed a find-and-replace paradigm analogous to Nardi et al. (2019). Without being told how to solve the task, participants had to find a target object that emitted a sound, encode its location, and after being disoriented, they had to replace it in the original location. Differently from previous studies on terrain slant, here we used a larger search space: the distance of the target from the starting location was more than three times longer compared to what was used in Nardi et al. (2019) (radius of 366 vs



Figure 1. Panel A: Broad view of the Ball State University campus lawn (the Quad) where the study took place. The location of the slanted testing site is marked with “b” and the flat testing site is marked with “c”. Panel B: Slanted site. The participant is shown searching for the target object (noise machine). Panel C: Flat site. The participant is shown during the disorientation procedure.

108 cm). Because of the larger scale of the explorable environment, rather than a reorientation task, we refer to the present as a place-learning task. In the present study, each participant was tested in two different sites (in counter-balanced order): a flat terrain (no incline) and an area presenting a modest incline (4°). There were several uncontrolled spatial cues available in both sites; e.g., the wind, the sun/shade, and possible sounds from people walking or car traffic. However, if terrain slant can be spontaneously used to navigate, we would expect better performance in the slanted site, as measured by significantly smaller errors.

2. Method

2.1. Participants

Thirty Ball State University students (17 females, 13 males) volunteered for this study in exchange for monetary compensation (\$15). Students were recruited by means of e-mails from the Ball State Communication Center and flyers posted in campus buildings. It was stated in advance that participants must be students 18 years old or older, with no impairments in vision, audition, balance, and mobility. Participants ranged from 18 to 25 years of age ($M = 20.9$; $SD = 1.9$). This study was approved by the Ball State University's Institutional Review Board (IRB #1475251-1).

2.2. Sites and target location

The place-learning task took place in a large grassy field, commonly referred to as the Quad, on the south end of Ball State University campus, surrounded on two sides by campus buildings and on two sides by low traffic streets. The Quad consists of large areas of lawn with a few sparse trees and paved pedestrian paths. Foot traffic in this area is light and mostly in between class times. Within the Quad, two testing sites were chosen ([Figure 1](#)). One site, called slanted testing site, presented a uniform 4° incline (measured with a SUUNTO PM-5/360 PC clinometer). The other site, called flat testing site, was located at the bottom of the incline and was level (no incline). Each site included a 732 cm radius of plain lawn, and centered in this, a search space of 366 cm radius for the place-learning task; a bar stool was placed in the center of the search space and was the starting location for the task (see [Figure 2](#)). If participants walked past the 732 cm radius, we planned to consider them out of bounds and stop them; however, this never happened. The two sites were 48 m distant from each other (measured from centers). Each participant was tested in both testing sites, in counterbalanced order across sexes.

The purpose of the place-learning task was to remember the location of a target object in the search space. The target was always placed on the ground

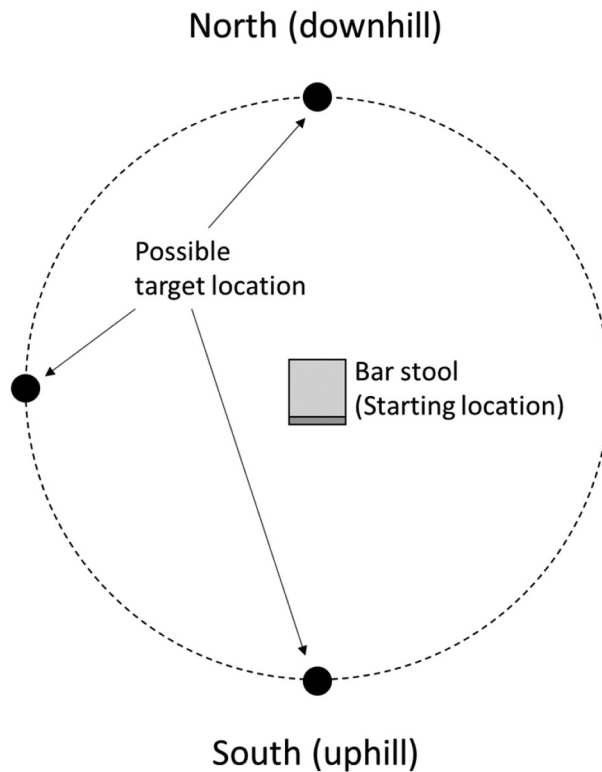


Figure 2. Schematic representation of the place-learning task. Three trials were carried out in each testing site (slanted and flat). The target (depicted here as a black circle) was always located 366 cm from the bar stool, in one of three possible positions (in counterbalanced order across participants): north, south, or west. Blindfolded participants had to find the target and, after being spun on the bar stool, replace it back where it used to be.

366 cm away from the bar stool. In the slanted site, relative to the starting location, the target could be placed uphill (which happened to be south), downhill (north), or across (west). In the flat site, the target could be placed south, north, or west. In each site, one trial was carried out for each target location (3 trials in each site), in counterbalanced order across sexes (see [Figure 2](#)).

All the testing equipment and the bar stool were placed in the testing sites only during a testing session. When not testing participants, there was no obvious sign that a study was taking place in those two sites.

2.3. Materials and stimuli

A bar stool (base: 16 cm diameter; seat height: 68 cm) with back and footrest was used to gently spin participants during the disorientation procedure; the stool was placed in the center of each site and was the starting location for the place-learning task. In the slanted testing site, a wooden wedge (45 cm x 45 cm;

4° angle) was placed under the base of the bar stool to compensate for the slanted terrain and allow the stool to be upright.

Two small noise machines with multiple types of sounds (Huawei model UNM-GH-006; diameter 13 cm) were used as auditory beacons. One noise machine was the target object to find and replace, and this was set on the ground in a predetermined location (see [Figure 2](#)); the selected sound was birds chirping. The second noise machine was placed in an open backpack (Daxvens; 43 cm x 30 cm) strapped to the back of the bar stool (starting location); the selected sound was soothing music. Sound-emitting beacons were used for the target and starting location because we wanted participants to easily home in on them, and we were interested in how the target would be encoded (it should be emphasized that the direction of the target cannot be remembered based on the starting location). These two sound samples were chosen because they were obviously distinct from each other, both were clearly audible in the environment, and both were constantly active (without long pauses). During the task, the volume of both noise machines was at the highest setting, which produced an intensity of approximately 65 dB measured from 366 cm away (REED Instruments R8050 sound level meter).

During the task, participants were required to close their eyes and wear a blindfold (Yuaury Sleeping Mask Padded Sleep Aid). They were provided with a walking cane (NO-JAB walking cane; 152 cm). Participants were asked to bring their own headphones for use during the disorientation procedure, and noise-canceling Bluetooth headphones (JLab, model B07R4BX9GW) were also available in case needed. A hand compass (SUUNTO KB-14/360 R G) was used during the slope identification task, when participants were asked to point to the uphill direction. A stopwatch (Accusplit Prosurvivor 601x) was used by the experimenter to time the participants.

2.4. Paper-and-pencil tests

After the outdoor task, participants returned to the lab and took two paper tests. The first was the Water-Level Test (WLT; Piaget & Inhelder, 1956); we used the test version devised by Liben (1995). This test assesses the use of the gravity reference frame for inferring the level of a liquid in a tilted bottle. There are 6 items, and the score can range from 12 (perfect score) to 0. This test was included because previous studies have shown a correlation with the use of terrain slope for spatial reorientation (Nardi et al., 2011, 2013).

The second test was the Wide Range Achievement Test, Word Reading Subtest (WRAT-4; Wilkinson & Robertson, 2006). This is a measure of verbal fluency/verbal intelligence. Participants are given a printed list of 55 words of increasing difficulty and are asked to pronounce them aloud. The experimenter is trained on the correct pronunciations (in American English) ahead of time and scores the accuracy of each pronunciation in real-time. The total

score is the number of correctly pronounced words out of the total (a perfect score is 55). This test was included as a measure of verbal and general intelligence (it correlates highly with the WAIS-III and WISC-IV; Strauss, Sherman & Spreen, 2006).

2.5. Procedure

The study was conducted by a team of two experimenters. Participants were tested individually. Participants were contacted to schedule the experimental session and were told in advance: *“in this study, you will have to complete a task outdoors that requires keeping your eyes closed and wearing a blindfold for the entire duration”*. The participant met the experimenters in a lab in the Psychological Science department (the building is on the Quad). After completing the consent form, they were led to the first testing site for the place-learning task. When walking from the lab to the first testing site, and then to the second testing site, the experimenters transported all the necessary equipment for the task on a wagon. No material was left on the testing sites between sessions.

2.5.1. First site

The participant was taken to the first site (either the slanted or flat site, in counterbalanced order). While one experimenter took care of the setup (put the bar stool in place, prepared the equipment), the other experimenter explained the place-learning task and allowed the participant to familiarize with the materials they would use (bar stool, cane, headphones with music). Importantly, they were shown the noise machine that constituted the target object and they were presented with the sound that it made (birds chirping). They were also shown the sound machine that was placed in the backpack strapped to the bar stool and they were presented with the sound that it made (soothing music). When ready, they were told to sit on the bar stool (starting location), close their eyes and wear the blindfold, and the first trial began.

2.5.2. Disorientation procedure

Participants were gently spun on the bar stool for 60 seconds, changing speed and direction of rotation. The maximum rotation speed was 12 r.p.m. The purpose was to disorient the participant so that they would lose awareness of which direction they are facing. During disorientation, and only during disorientation, participants wore headphones with preset music of their choosing. The facing orientation of the bar stool at the end of each disorientation procedure could be north, west, south, or east, chosen according to a pre-established random sequence. After each disorientation procedure, the participant took off the headphones (and turned off the music), stood up, and was given the cane. At this point, they were asked to walk a full circle holding

a hand on the back of the bar stool. The purpose was to ensure they would sample the environmental cues before leaving the starting location.

2.5.3. Finding the target

During disorientation, one experimenter placed the target object (noise machine) in the assigned location and turned on its sound (birds chirping). Guided by the sound, and using the cane as an aid for walking, the participant was told to find the target object and remember its location. Once they found it, they picked it up from the ground and, when ready, gave it to one experimenter (who turned it off). At this point, guided by the sound coming from the bar stool, the participant walked back to the bar stool. They sat on the stool and another disorientation procedure, identical to the one described above, followed. This eliminated the possible use of path integration to encode the target location.

2.5.4. Replacement

Next, the experimenter turned on the sound of the target object and handed it to the participant. They were told to place it back where it had been. They were told that accuracy was the most important thing, but that they would also be timed. Timing started when they were handed the target and ended when they replaced it on the ground. Immediately after the target was replaced, one experimenter measured (with a tape measure) the replacement error, i.e., the straight-line distance between the replaced location and the correct location of the target.

2.5.5. Feedback

While one experimenter measured the replacement error, the other experimenter placed the target object back in the correct location. The participant was told that the target was now being placed where it used to be, and they were asked to reach it so they would know how accurate they had been (correction procedure). This feedback was provided to discourage participants from potentially using unreliable cues, such as path integration (trying to maintain orientation by keeping track of how they were spun on the bar stool). When the participant picked up the target, they handed it to one experimenter (who turned it off) and then walked back to the bar stool. This concluded the first trial.

The same procedure (disorientation, finding the target, disorientation, replacement, and feedback) was followed for two more trials (total of three trials), with the target object placed in a different location in each trial (counterbalanced order across sexes). At the end of the third trial, the task in the first site was over. The participant removed the blindfold and walked with the experimenters to the second site.

2.5.6. Second site

The procedure of the task in the second site (flat or slanted site, whichever was not used for the first site) was the same as that in the first site, with the following exception. At the end of the third and last trial, while standing at the corrected location of the target, the participant took the slope identification task.

2.5.7. Slope identification task

Without taking off the blindfold, the participant was given a hand compass and allowed to practice pointing with it. They were told that they would be asked questions and to point to an object with the compass. They had to hold the compass with one hand and extend the whole arm when pointing. The experimenter also said that there was no time limit, but they would be timed. The first question was: *“Is the ground slanted or horizontal?”*. Timing started at the end of the question and ended as soon as the participant responded. If the participant answered “slanted”, they were told: *“Now please indicate the uphill direction by pointing with the compass, and say done when you are sure”*. Timing started at the end of the question and ended when they said done. The absolute (unsigned) angular error between the pointing direction and the correct uphill direction was calculated. The slope identification task was carried out only at the second site in order to not draw attention to the terrain.

After this, they removed the blindfold and were asked *“What information or strategy were you using to remember where the target was and to put it back in place?”*. This concluded the outdoor portion of the study. After this, the participant and the equipment were taken back to the lab.

2.5.8. Follow-up

In the lab, the participant first took the WLT and then the WRAT. Then they were given a demographic questionnaire in which participants were asked to report age, sex, year in college, average weekly hours of physical activity, height and weight, and any impairments. Finally, participants were debriefed and paid 15 USD cash.

The entire experimental session for a participant took approximately 1 hour to complete. Participants were frequently asked if they were feeling well during the study. No participant ever reported feeling light-headed, dizzy, or ill during disorientation or any other procedure.

2.6. Data analysis

The main dependent variable for the place-learning task was the replacement error, defined as the straight-line distance between the correct location of the target and where it was replaced by the participant. This was submitted to a 2

(between: sex) x 2 (within: slanted or flat terrain) x 3 (within: trial) mixed ANOVA. An analogous ANOVA was carried out on the time taken to replace the target.

The average replacement error was compared to a baseline level of error assuming that participants encoded the distance of the target, but not its direction, from the starting location (bar stool). Because the target was at a fixed distance from the starting location in all trials (366 cm), we assumed that if a participant encoded the distance (but was guessing the direction) they would replace the target on a circumference of 366 cm radius from the starting location. Assuming a random, uniform distribution of replacements along such circumference, we calculated that the average replacement error (corresponding to the target being replaced 90° to the left or right of the correct location) would be 518 cm. This value will be referred to as baseline level of error (for a schematic representation see [Figure 2](#)). One-sample t-tests were carried out to assess if average errors deviated significantly from this baseline.

Our sample size was too small to consider sex differences appropriately. However, because they have often been found in navigation (for a recent review see Nazareth, Huang, Voyer & Newcomb, 2019), and specifically with slope use (Holmes et al., 2015; Nardi et al., 2011), sex was added as an independent variable in the main analyses.

3. Results

3.1. Place-learning task

In the place-learning task, the replacement errors were analyzed with a 2 (sex) x 2 (slanted or flat terrain) x 3 (trial) mixed ANOVA. There was a significant main effect of terrain, $F(1, 28) = 10.973$, $p = .003$, $\eta_p^2 = .282$. Participants made smaller errors in the slanted site ($M = 411$ cm; $SEM = 37$) than in the flat site ($M = 532$ cm; $SEM = 31$). There was not a significant main effect of sex, $F(1, 28) = .047$, $p = .830$, $\eta_p^2 = .002$. Male and female participants did not display significantly different accuracies. Also, there was not a significant main effect of trial, $F(2, 56) = .752$, $p = .476$, $\eta_p^2 = .026$. Errors did not vary significantly across trials. All interactions were not significant, $ps > .228$. Means and SEM are shown in [Figure 3](#).

Average replacement errors were compared to a baseline level of error (518 cm) assuming encoding of distance – but not direction – of the target from the starting location (bar stool). One-sample t-tests revealed that average errors were significantly smaller than baseline in the slanted site, $t(29) = -2.944$, $p = .006$, $d = .54$, but not in the flat site, $t(29) = .391$, $p = .699$, $d = .07$. When considering sexes separately, in the flat site, the average errors for both males ($M = 545$ cm; $SEM = 48$; $t(12) = .555$, $p = .589$, $d = .15$) and females ($M = 519$ cm; $SEM = 41$; $t(16) = .020$,

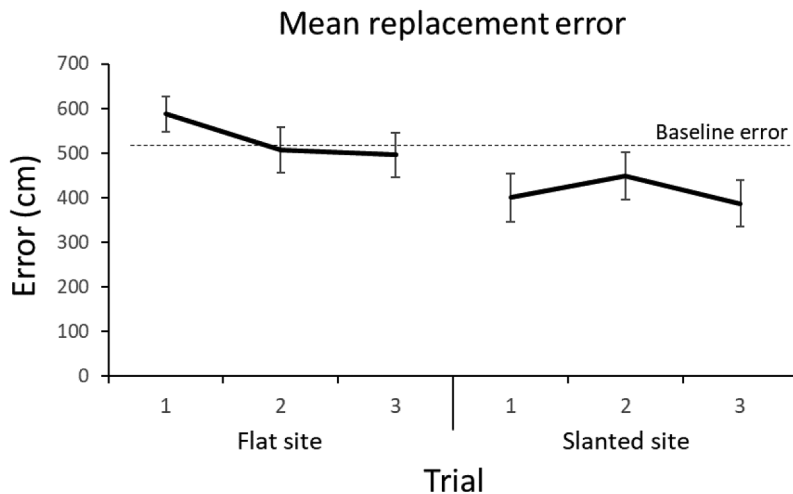


Figure 3. Mean replacement error ($\pm$ SEM) for each trial in the flat and slanted site. Note that participants were tested in each site in counterbalanced order across sexes. The average error was significantly smaller in the slanted site than the flat site. There was no significant effect of sex or trial, and no interactions were significant. The dashed line represents a baseline level of error (518 cm) assuming encoding of distance – but not direction – of the target from the starting location. The replacement error was significantly smaller than the baseline in the slanted site, but not in the flat site.

$p = .984$, $d = .01$) were not significantly different from baseline. In the slanted site, the average errors for males were significantly smaller than baseline ($M = 411$ cm; $SEM = 47$; $t(12) = -2.292$, $p = .041$, $d = .64$); females' errors were marginally, but not significantly, smaller than baseline ($M = 412$ cm; $SEM = 54$; $t(16) = -1.960$, $p = .068$, $d = .48$).

The time taken to replace the target was analyzed with a 2 (sex) $\times$ 2 (slanted or flat terrain) $\times$ 3 (trial) mixed ANOVA. There was a significant main effect of sex, $F(1, 28) = 10.873$, $p = .003$, $\eta_p^2 = .280$. Male participants ($M = 11.2$ s; $SEM = 1.0$) completed the task significantly faster than females ($M = 15.7$ s; $SEM = .9$). There was not a main effect of terrain, $F(1, 28) = .013$, $p = .912$, $\eta_p^2 < .001$. Participants did not replace the target more quickly in one site compared to the other. There was also not a main effect of trial, $F(2, 56) = 2.394$, $p = .101$, $\eta_p^2 = .079$. Replacement time did not vary significantly across trials. No interactions were significant, $ps > .302$.

3.2. Slope identification task

One participant's data in the slope identification task were accidentally not recorded ($N = 29$). In the second testing site (which could have been flat or slanted, in counterbalanced order), participants were first asked whether the ground was slanted or horizontal. When the terrain was actually flat ($n = 14$), 8 participants answered correctly (57.1%); this proportion was not significantly

different from 50–50 guessing (binomial test, 8 vs 6, $p = .791$). When the terrain was actually slanted ($n = 15$), 12 participants answered correctly (80.0%); this proportion was significantly better than chance (binomial test, 12 vs 3, $p = .035$). When comparing the RT to respond, participants were significantly faster when the terrain was slanted ($M = 2.4$ s; $SEM = 1.0$) than when it was flat ($M = 6.7$ s; $SEM = 5.5$), $t(27) = 2.978$, $p = .006$, $d = .98$. Overall, when the terrain was slanted, participants could recognize it as such and were more confident in their responses; however, when the terrain was flat (no incline), it was more difficult to recognize it confidently as such.

If participants answered “slanted” to the first question, they were asked to indicate the uphill direction by pointing with the compass. We considered the cases in which the terrain was actually slanted ($n = 12$), and we calculated the absolute, unsigned angular error from the correct uphill direction (0° error would be a perfect score, i.e., pointing exactly uphill; 180° would be the largest possible error, i.e., pointing downhill; 90° would be the average error, considered chance). The mean angular error was 41.7° ($SEM = 10.5$), which was significantly smaller than chance, $t(11) = -4.601$, $p = .001$, $d = 1.33$. Participants could identify the uphill direction of the slanted site above chance level. When we examined whether there was a correlation between this uphill-pointing angular error and the average error in replacing the target in the place-learning task (averaged across the three trials in the slanted site), the correlation was not statistically significant, $r(10) = -.001$, $p = .999$.

3.3. Self-reported strategy use

At the end of the task, when participants were asked what strategy they used to remember the location of the target, they reported multiple cues. Eleven participants (36.7%) mentioned tracking the spinning of the bar stool during the disorientation procedure, as if they attempted to remain oriented. Nine participants (30.0%) mentioned that they used the slant of the ground. Eight participants (26.7%) mentioned using various sounds/noises (target, bar stool, or other uncontrolled environmental sounds), 8 participants (26.7%) mentioned using the heat from the sun felt on their faces, and 5 participants (16.7%) mentioned using the wind. Considering the average replacement error in the slanted site, participants who mentioned using the slant ($n = 9$; $M = 385$ cm; $SEM = 71$) did not have significantly different errors compared to those who did not mention the slant ($n = 21$; $M = 423$ cm; $SEM = 43$), $t(28) = .471$, $p = .641$, $d = .19$. Explicit reporting of slant use was not associated with better performance.

Finally, 16 participants (53.3%) reported counting the steps to the target, suggesting that they explicitly encoded the target distance from the starting location in this way.

4. Correlations

In order to gain insight into the individual differences in performance in the place-learning task, we examined if the error or RT in replacing the target (averaged across the three trials in the slanted site) correlated with performance in the WLT, WRAT, or with demographic variables (average hours of activity per week, height, and weight). There was a non-significant correlation that approached $\alpha = .05$ between average RT and WRAT, $r(28) = -.352$, $p = .057$ (higher WRAT scorers tended to be faster). For all other correlations $ps > .221$. Previous studies have shown an association between the WLT and the use of slope for reorientation (Nardi et al., 2011, 2013), which suggests an ability to use the gravity reference frame; an intriguing possibility is that such a correlation was not found in the present study because, unlike those experiments, this was a nonvisual task.

5. Discussion

Participants were able to encode the target location and replace the target with significantly smaller errors in the slanted site than the flat site, suggesting that the terrain slope aided place learning. Furthermore, performance in the flat terrain site did not deviate significantly from what would be expected if participants encoded only the distance of the target from the starting location, but not its direction. This indicates that on the flat terrain participants could not use uncontrolled cues (such as the sound of people walking, car traffic, the sensation of wind, sun, etc.) to solve the task. Conversely, in the slanted site, the performance was significantly better than what would be expected if guessing the direction of the target. This supports the fact that, because of the slant, participants encoded the direction of the target and restricted their responses around this. It should be noted that the slanted site presented only a 4° slope (1:14 or 7% grade); to give a term of comparison, the maximum slope of wheelchair ramps according to current ADA standards (Americans with Disability Act of 1990) is 4.8° (1:12 or 8% grade). Overall, these findings suggest that the presence of even a gentle hill provides people with a useful directional cue (Jacobs & Schenk, 2003) that can guide behavior.

Importantly, the slope was used spontaneously in our study. Participants were not instructed to use any particular cue (open task); they had to detect the presence of the slope, focus on it (and ignore other cues with no predictive value), and use it to guide their behavior. In similar types of open tasks, sighted participants seem to have difficulty encoding a target location when visual cues are impoverished or completely absent. For example, in the first study on human reorientation with slope, large individual and sex differences were found when participants were not informed which cue to use, with many failing the task (Nardi et al., 2011). Participants were not blindfolded, but the visual cues were inconspicuous. Rather

than being guided by floor slant, many participants at the end of the study reported attempting to keep track of how they were being spun during disorientation (path integration), which is very difficult to do and leads to at-chance performance. Other participants reported using uncontrolled, idiothetic, unsuccessful – and quite surprising – cues (e.g., the inclination of the incandescent filament in light bulbs at the corners of the enclosure). Task accuracy improved when participants were explicitly told in advance to use the slope. Despite the difficulty of using floor slant for some, on average participants performed better than chance. In a more dramatic case, sighted participants completely failed to reorient in an open task if blindfolded and provided with auditory landmarks (Nardi et al., 2019). This occurred even when the auditory landmark offered non-ambiguous information and was the only predictive cue in the environment. Again, many participants attempted to use path integration or other uncontrolled cues, which led to at-chance performance. An analogous resistance to using auditory cues has been found in Nardi et al. (2020), where a quarter of the participants used path integration even though explicitly discouraged from doing so. Therefore, it should not be taken for granted that a sighted person will spontaneously identify and rely on a nonvisual cue for a spatial task, even if the cue is informative and reliable. The modest slope in the present study was salient enough to be noticed and used.

Even though terrain slant guided place learning, the self-reports at the end of our study showed that only 30% of the sample mentioned using slope as a strategy. Many other uncontrolled cues were mentioned too, even though they did not successfully guide behavior (if the uncontrolled cues had actually been good predictors of the target location, then the average replacement error in the flat site should have been significantly smaller than baseline). Interestingly, the participants who mentioned using slope did not perform significantly better in the task. These findings may suggest that, overall, the slope was used but not necessarily explicitly. Some participants might have thought they were using a different cue, when they actually were relying on terrain slant. The dissociation between spatial behavior and explicit awareness of the guiding strategy has also been found with auditory cues (Nardi et al., 2020). It seems that in some cases spatial cues might be relied upon implicitly by sighted persons. This would probably contrast with persons who are blind or visually impaired, as they are used to being explicitly aware of the strategies adopted for navigating (Giudice, 2018).

What does this study tell us about the differences and similarities between nonvisual-based and visual-based spatial learning? A systematic comparison cannot be made because we did not have a visual-encoding condition in our task; however, at least one finding from our study should be highlighted that seems at odds with the evidence gathered using visual cues. Replacement errors in our task were very large. The average linear error in the slanted site was 4.12 m relative to a search space of 7.32 m in diameter (approximately 56%). The slant of the terrain provided participants with a directional type of cue (e.g.,

uphill or downhill), which can be used to establish facing direction and course, but not distance to a target (Chai & Jacobs, 2009; Jacobs & Schenk, 2003). In this sense, our task is equivalent to some visual goal-localization tasks using virtual environments in which visual landmarks (like mountains) are projected at infinity in the horizon and can be used only to determine a direction of reference (e.g.; Chai & Jacobs, 2009; Doeller & Burgess, 2008; Doeller, King & Burgess, 2008). For example, in Doeller and Burgess (2008), participants had to encode the location of a few objects and then replace them in the virtual environment. In one of the simplest experimental conditions, the average linear error was approximately 15 m relative to a search space of 180 m in diameter (approximately 8%). Obviously there are considerable differences in method and procedure (most notably the locomotion in virtual vs real environment), but the different order of magnitude of the errors seems to suggest that accuracy in our study was low compared to visual-based tasks. A previous study on reorientation in a circular search space also reported very large errors for blindfolded, sighted participants using slope (average angular error of 59°, on a scale from 0°, perfect response, to 180°, maximum error; Nardi et al., 2019). In contrast, the average angular error using visual cues is much smaller (only 1°; Twyman, Holden & Newcombe, 2018). The lower accuracy in place learning guided by slope is probably related to the difficulty identifying nonvisual spatial sources with precision. It is well known that localizing an auditory source in the environment typically presents larger errors (approximately 7°; Blauert, 1997) than a visual source. Similarly, it has been found that the average error identifying the uphill direction of a 4° indoor ramp by blindfolded, sighted participants is comparatively large (approximately 19°; Nardi et al., 2019). In the present study, the average error judging the uphill direction of an equivalently gentle incline (slope identification task) was approximately twice as large (41.7°), probably because of greater uncertainty sensing an outdoor terrain than a smooth ramp. If we modeled performance in our place-learning task only based on this error related to perceiving the slant (i.e., not taking into account other possible sources of errors, such as those related to memory of the target location, cue integration, decision making, and motor execution), then the average replacement error would be 2.61 m (approximately 36% of the search space). This replacement error is smaller than what was actually observed, but it is still considerably larger than what reported in the visual-based tasks mentioned above (Chai & Jacobs, 2009; Doeller & Burgess, 2008; Doeller et al., 2008). In sum, our study indicates that, for sighted people, proprioceptive/kinesthetic and vestibular access to a slanted environment supports place learning, but probably with lower accuracy compared to a visually accessed environment.

In conclusion, this outdoor field experiment suggests that terrain slant is an environmental cue that is realistically used for place learning – not just in lab settings. It is used spontaneously, albeit sighted participants might not always be aware of relying on it and might use it with low accuracy. Therefore, slope can be

added to the list of other ecologically relevant sources of spatial information for humans, along with visual landmarks and geometry (Cheng, Huttenlocher & Newcombe, 2013; Gallistel, 1990; Stürzl, Cheung, Cheng & Zeil, 2008), sounds and language (Loomis et al., 1998; Nardi et al., 2020; Viaud-Delmon & Warusfel, 2014), tactile cues (Giudice & Legge, 2008; Sturz et al., 2014), etc. The present study involved a larger search space (approximately 3 times larger) compared to some previous experiments on slope (Holmes et al., 2015; Nardi et al., 2019, 2011, 2013). However, it would be important to know if terrain slant can help navigation in more complex and larger environments, where the destination is not perceivable from the starting location. To the best of our knowledge, this has been confirmed in virtual environments, with only visual information (Weisberg & Newcombe, 2014) or visual plus haptic feedback (Restat, Steck, Mochnatzki & Mallot, 2004). If this occurs even with only proprioceptive/kinesthetic access to the environment, it would highlight the potential usefulness of slope for visually impaired persons. To the best of our knowledge, no study has systematically tested blind or visually impaired participants for the ability to use terrain slope. This could speak to issues related to sensory substitution, experience, and awareness with different spatial cues for blind and sighted persons. Is slope used more easily and proficiently by blind navigators? We might find that terrain slant should be referenced more frequently in maps, signs, and mobility aids because of its potential salience. The topography of the land provides a suite of spatial information; visual cues should not be the only focus.

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Availability of Data and Material

The datasets collected and/or analyzed during the current study are available from the corresponding author upon request.

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