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BRIEF REPORT

Head for the hills: The influence of environmental slant on spatial memory organization

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Abstract Environmental slant is known to improve navigation performance in humans and other animals. Successful navigation relies on accurate spatial orientation and accurate spatial memory retrieval. The role of environmental slant in spatial orientation has been established, but its role in spatial memory organization is unclear. Two experiments using immersive virtual reality explored the influence of environmental slant on reference frame selection during spatial learning. Participants studied object locations on a sloped surface. When no additional environmental cues were present (Experiment 1), spatial memory retrieval was best from the studied perspective aligned with the direction of slope. When the direction of slope was placed in competition with the axis of the surrounding room (Experiment 2), spatial memory retrieval was best from the initially studied perspective. The latter finding contrasts with the results of research showing that pigeons preferentially rely on environmental slant over room shape. The findings are discussed in the context of spatial memory theory.

Keywords Spatial memory · Environmental slant · Reference frame

Spatial behaviors such as finding one's car in a parking lot depend on successful spatial memory retrieval. Because locations are inherently relative, they must be remembered in the context of a spatial reference system, or reference frame. Spatial memory retrieval (e.g., imagined perspective-taking) is typically best from one or two perspectives, which is thought to represent the underlying reference frame structure (Klatzky, 1998). Reference frame selection is influenced by experiential and environmental cues during learning. Environmental cues such as city streets (Werner & Schmidt, 1999) and room walls (Shelton & McNamara, 2001) often result in the selection of reference frames aligned with environmentally defined axes, especially when experienced perspectives are aligned with environmental axes.

Environmental slant (herein defined as changing elevation across a surface) is a salient spatial cue with perceptual and behavioral implications: Undulating terrain can occlude parts of the environment, and hills present physical challenges for locomotion. Navigation within a city results in incidental encoding of relative elevation (Garling, Book, Lindberg, & Arce, 1990), indicating the salience of slant during spatial learning. Despite this evidence that slant is encoded in memory, it is unknown whether elevations are simply associated with locations or whether environmental slant influences the reference frame structure of spatial memory. The present project investigates environmental slant as a cue to reference frame selection.

Anecdotal evidence for the salience of slant comes from research on native speakers of Mayan Tzeltal, who live in mountainous terrain in southern Mexico. When describing locations, speakers of Tzeltal make almost exclusive use of an absolute reference system centered on the environmental slant that characterizes the region (Brown & Levinson, 1993). The most common Tzeltal terms when describing spatial relationships are “uphill,” “downhill,” and “across,” reflecting the salience of environmental slant in determining the reference frame used to describe space.

Research on navigation indicates that humans make use of environmental slant when moving through the environment. In one study, participants learned locations within a virtual town built on a flat or sloped surface (Restat, Steck, Mochnatzki, & Mallot, 2004). Subsequent navigation to

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remembered locations was more accurate in the sloped town than in the flat town. Furthermore, pointing to unseen locations was more accurate in the sloped town than in the flat town. However, it is unclear whether superior navigation and pointing performance in the sloped town was due to more accurate spatial memories or better spatial orientation in the presence of environmental slant. Both tasks required participants to determine their current position and orientation within the virtual environment and then retrieve a remembered goal location relative to their position and orientation. There is ample evidence that environmental slant facilitates spatial orientation (Chai & Jacobs, 2010; Nardi, Newcombe, & Shipley, 2010, 2011), but comparatively little evidence that slope influences the organization of spatial memories.

The present experiments were designed to assess the influence of environmental slant on the reference frame organization of spatial memory. Research on environmental slant has typically focused on large spaces that cannot be apprehended from a single perspective (e.g., Restat et al., 2004), whereas research on reference frames in spatial memory has typically used smaller spaces, visible from a single perspective (e.g., Shelton & McNamara, 2001). To understand the influence of environmental slant on spatial memory organization, the present experiments used relatively small environments for comparison with past research on reference frames in spatial memory.

In these experiments, spatial layouts were learned in immersive virtual reality (VR). Three-dimensional virtual environments were experienced through a head-mounted display (HMD), and movement was achieved by physically walking and turning. VR has previously been used to replicate and extend real-world spatial memory research (Kelly, Avraamides, & Loomis, 2007; Kelly & McNamara, 2008).

Experiment 1

Experiment 1 was designed to assess the influence of environmental slant on reference frame selection when object locations were learned in a virtual environment. Participants studied objects placed on a slanted table in an otherwise empty environment. Studying occurred from two perspectives, separated by 135°, and study-perspective order was manipulated. The table sloped downward toward one of the two studied perspectives. If environmental slant influences reference frame selection, object locations should be remembered using a reference frame aligned with the slope of the table,[1] regardless of study-perspective order (similar to the influence of room shape; Shelton & McNamara, 2001). If environmental slant does not influence reference frame selection, participants should select a reference frame from the initial study perspective (similar to learning in a circular environment; Kelly et al., 2007).

Method

Participants Eighteen men and 18 women participated for course credit. Data from 2 men and 2 women were discarded due to average errors larger than 65° (a predetermined performance criterion).

Stimuli and design Learning stimuli were presented using an nVisor SX111 HMD (NVIS, Reston, VA), which presented stereoscopic images at 1,280 × 1,024 pixel resolution. Field of view was 102° horizontal × 64° vertical. Head orientation was tracked using a three-axis orientation sensor (InertiaCube2+ from Intersense, Bedford, MA), and head position was tracked optically (PPTX4 from WorldViz, Santa Barbara, CA). Graphics presented through the HMD were updated at 60 Hz and reflected changes in the participant's head position and orientation. Graphics were rendered using Vizard software (WorldViz, Santa Barbara, CA) running on a computer with Intel Core2 Quad processors and a Nvidia GeForce GTX285 graphics card.

The learning environment consisted of eight objects (lamp, car, train, cup, hat, plant, apple, and ball) on a round table (100-cm radius) placed on an infinitely large grassy plane. Objects were scaled to fit within a 30-cm^3 volume. The object layout (Fig. 1a) was similar to that used in previous research (e.g., Mou & McNamara, 2002). The tabletop surface was slanted 15° and was 20 cm from the ground at its lowest point and 74 cm at its highest point. The table sloped downward toward 0° or 135°, and slope direction was manipulated between participants.

Participants studied the layout from two perspectives, 0° and 135° (Fig. 1b,c). Study-perspective order was manipulated between participants. After learning, participants moved to another room to perform judgments of relative direction (JRDs) and draw a map of the layout. JRDs required participants to imagine standing at one object, facing a second object, and point toward a third object from the imagined perspective, using a joystick. JRDs tested eight perspectives (every 45° from 0° to 315°). For each imagined perspective, eight trials were constructed requiring correct egocentric pointing responses spaced every 45° from 0° to 315° to control for the front facilitation that occurs when locations in front of the imagined perspective are pointed to (Kelly & McNamara, 2009). Dependent measures for JRDs were error and latency.

After completing all JRDs, participants were provided with a rectangular paper on which to draw the remembered

[1] Alignment is considered relative to the up–down axis, which is perceptually and biomechanically more salient than the orthogonal axis.

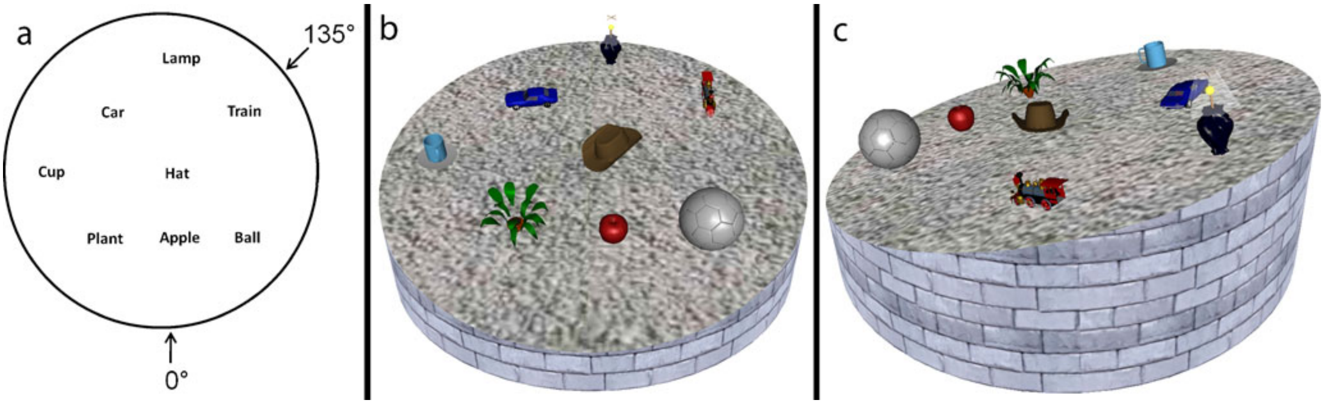

Fig. 1 Object layout used in Experiment 1; arrows indicate the two studied perspectives (**a**). Perspective images from the 0° (**b**) and 135° (**c**) study perspectives show the sloped table. The textured ground plane has been removed for publication

layout. Instructions at the top of the paper directed participants to mark each object location with an "X" and to write the object's name next to its location. The dependent measure for the map-drawing task was the orientation from which the map was drawn.

Procedure Participants donned the HMD while standing halfway between the 0° and 135° study perspectives. When the display was turned on, the participants saw the sloped table from this intermediate perspective, but none of the objects were visible. Participants were led to the 0° or 135° study perspective, depending on condition. Eight objects appeared on the table, and the experimenter named each object in a random sequence. Participants studied the objects for 30 s, after which the objects disappeared and the participants attempted to point toward each object in an order determined by the experimenter. After the study-then-point procedure had been completed three times, the objects were hidden from view, and the participants were led to the second study perspective where the learning procedure was repeated. The HMD was removed after learning was complete.

Participants were led to another room where they completed questionnaires about spatial abilities and demographic information. The questionnaires were intended to occupy working memory resources to prevent participants from retaining a visual image of the most recently experienced view in working memory. Participants then performed three practice JRDs, which allowed the experimenter to verbally verify that they understood the task. Participants then completed 64 JRDs in a random sequence. Responses were recorded when the joystick was deflected by 30° from vertical. After completing all JRDs, participants drew a map of the objects.

Analysis Facilitated JRDs performance from one or more imagined perspectives is considered evidence that spatial memory was organized around a reference frame along the facilitated perspective(s) (Klatzky, 1998). The primary goal during analysis was to determine which experienced perspective corresponded to the reference frame used to remember the layout. Data were analyzed in omnibus ANOVAs, followed by contrasts targeting the studied perspectives (0° and 135°), to test the a priori hypothesis that performance would be best when imagining the studied perspective aligned with the slope. Contrasts excluded nonexperienced perspectives because the conditions causing facilitation at novel imagined perspectives orthogonal to the reference direction are unclear, occurring in some studies, but not in others.

Maps were independently rated by two experimenters, blind to condition, to assess the orientation from which each map was drawn. Map orientations were scored to the nearest 45° from 0° to 315°. Discrepancies between experimenter ratings were resolved through discussion.

Results

Pointing error was more responsive to the independent variables than was latency, and there was no indication of a speed–accuracy trade-off: Within-participant correlations between latency and error averaged .27 (SD = .31), significantly above zero, $t(31) = 4.87$, $p < .001$. For brevity, the focus is on errors.

Regardless of study-perspective order, absolute pointing errors (Fig. 2) were smaller when the studied perspective aligned with the slope was imagined (M = 30.53°, SE = 3.26°), as compared with the studied perspective misaligned with the slope (M = 41.50°, SE = 3.93°). This conclusion was supported by statistical analyses. Pointing error was analyzed in a mixed-model ANOVA with terms for slope orientation, study-perspective order, and imagined perspective. The main effect of imagined perspective was significant, $F(7, 196) = 7. 40$, $p < .001$, $\eta_p^2 = .21$. No other

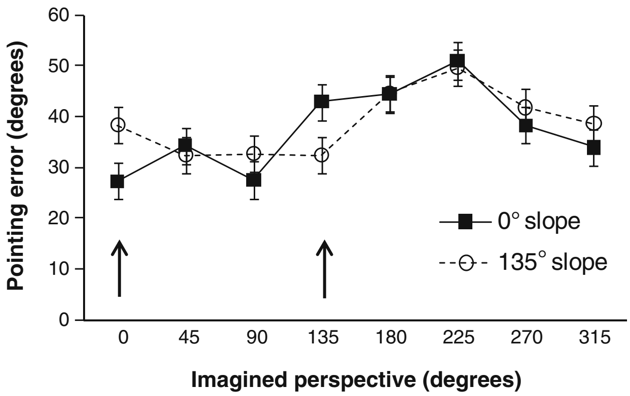

Fig. 2 Absolute pointing error in Experiment 1 as a function of imagined perspective and slope orientation. Error bars are standard errors estimated from the ANOVA. Arrows indicate the two studied perspectives

main effects or interactions reached significance. The a priori hypothesis that performance would be best when the studied perspective aligned with the slope was imagined was supported by the significant interaction contrast comparing performance at the two studied perspectives across the two slope orientations, $F(1, 28) = 6.17$, $p = .019$, $\eta_p^2 = .18$.

Map orientations are presented in Table 1. Interrater reliability was high (Cohen's kappa=0.89). Regardless of study-perspective order, maps were most often drawn from the studied perspective aligned with the slope. This conclusion was supported by statistical analyses. Map orientation was analyzed in a factorial ANOVA with terms for slope orientation and study-perspective order. Only the main effect of slope orientation was significant, $F(1, 28) = 15.00$, $p = .001$, $\eta_p^2 = .35$, reflecting participants' propensity to draw maps from the studied perspective aligned with the slope: 23 out of 32 participants drew their maps from this perspective.

Discussion

Memories for locations of objects on a sloped table were organized around a reference frame aligned with the slope orientation, indicating the relevance of slope as a cue to reference frame selection. After studying from two perspectives, one aligned and one misaligned with the slope, participants were better at imagining the perspective aligned with the slope, regardless of which perspective was studied first. These findings closely parallel those of previous studies in which objects in a rectangular room studied from multiple perspectives were remembered using a reference direction parallel to the room axis (Shelton & McNamara, 2001). Furthermore, orientations of map drawings were consistent with the pointing results, whereby maps were typically drawn from the studied perspective aligned with the slope of the table.

Experiment 1 demonstrated that environmental slant can influence reference frame selection during spatial learning, similar to other known cues, such as room shape (Shelton & McNamara, 2001), layout structure (Mou & McNamara, 2002), and object orientation (Marchette & Shelton, 2010). Despite the apparent functional similarity between different environmental cues, research on pigeons indicates that environmental slant receives greater weighting than do other environmental cues. In one study (Nardi, Nitsch, & Bingman, 2010), pigeons learned to locate a goal in the context of multiple environmental cues: the shape of the enclosure walls and the slant of the enclosure floor. Shape indicated the correct goal location on all learning trials, but slant direction varied during learning such that it correctly indicated the goal location on 33% or 50% of learning trials. Subsequent testing indicated that pigeons' responses were driven primarily by slant and secondarily by shape, even though slant was a less reliable indicator of goal location.

Animal research on environmental slant as a spatial cue indicates that slant is prioritized over other cues, including shape. Experiment 2 explored the relative influences of slant and shape (a known cue to human reference frame selection; Shelton & McNamara, 2001) on human spatial memory organization.

Experiment 2

Experiment 2 was designed to assess the relative influences of environmental slant and shape on reference frame

Table 1 Frequencies of map orientations drawn by participants. Orientations are presented separately for the two slope orientations in Experiment 1 and the two study-perspective orders in Experiment 2

	Map Orientation							
	0°	45°	90°	135°	180°	225°	270°	315°
Experiment 1								
0° slope	12	1	1	2	0	0	0	0
135° slope	4	0	0	11	1	0	0	0
Experiment 2								
0°, then135°	6	0	1	3	0	0	0	0
135°, then0°	1	0	0	9	0	0	0	0

selection. Participants learned locations of objects on a slanted table within a rectangular room. Slant orientation was placed in conflict with the long axis of the room. All participants studied the layout from two perspectives, one aligned with the table slant and one aligned with the room axis, and study-perspective order was manipulated. If environmental slant is a more salient cue than room shape, participants should remember the object locations using a reference frame aligned with the slope of the table. If environmental shape is more salient than slant, participants should select a reference frame aligned with the room axis. If neither slant nor shape dominates reference frame selection, performance should be best from the initially studied perspective, similar to past spatial memory research employing conflicting environmental cues (Kelly & McNamara, 2008; Shelton & McNamara, 2001).

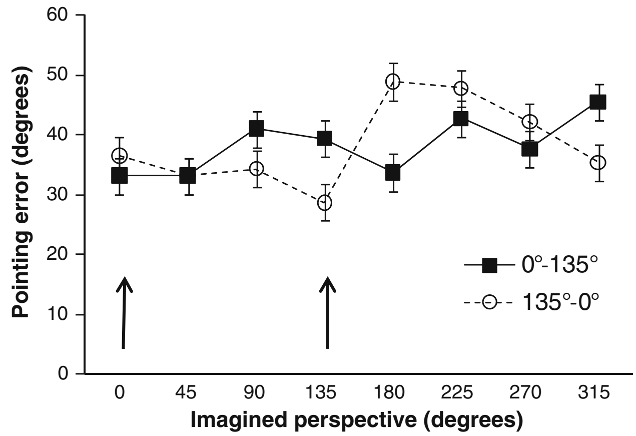

Fig. 3 Absolute pointing error in Experiment 2 as a function of imagined perspective and study-perspective order. Error bars are standard errors estimated from the ANOVA. Arrows indicate the two studied perspectives

Method

Participants Eleven men and 13 women participated for course credit. Data from 1 man and 3 women were discarded due to average errors larger than 65°.

Stimuli, design, and procedure Learning stimuli from Experiment 1 were modified by adding a surrounding rectangular room (8 × 5.25 m). The long axis of the room was parallel to the 0°–180° axis of the layout. The table sloped downward toward the 135° perspective, making the slope axis incongruent with the room axis. Study-perspective order (0°–135° or 135°–0°) was manipulated between participants. The stimuli, design, and procedure were otherwise identical to those in Experiment 1.

Results

Pointing error was more responsive to the independent variables than was latency, and there was no indication of a speed–accuracy trade-off: Within-participant correlations between latency and error averaged .03 (SD = .44), not significantly different from zero. For brevity, the focus is on errors.

Pointing errors (Fig. 3) were lower when the first studied perspective was imagined, as compared with the second studied perspective, regardless of alignment with the slope or the room. This conclusion was supported by statistical analyses. Absolute pointing error was analyzed in a mixed-model ANOVA with terms for study-perspective order and imagined perspective. A marginally significant main effect of imagined perspective, $F(7, 126) = 1.86$, $p = .082$, $\eta_p^2 = .09$, was qualified by a significant interaction between imagined perspective and study-perspective order, $F(7, 126) = 2.09$, $p = .049$, $\eta_p^2 = .10$, reflecting the superior pointing performance when imagining the initially studied perspective ($M = 30.94°$, $SE = 3.66°$), as compared with the second perspective ($M = 37.97°$, $SE = 3.55°$).

Map orientations are presented in Table 1. There were no discrepancies between the two raters (Cohen's kappa = 1.0). Maps were most often drawn from the first studied perspective, regardless of alignment with the slope or the room. This conclusion was supported by statistical analyses. Map orientation differed significantly across study-perspective order, $t(18) = 2.92$, $p = .009$, reflecting participants' propensity to draw maps from the initially experienced perspective: 15 out of 20 participants drew their maps from the first study perspective.

Discussion

Incongruent axes defined by the table slant and room shape resulted in spatial memories organized around a reference frame selected from the initially studied perspective. Pointing performance was best from the perspective aligned with the initial study perspective, and maps were also drawn from the initial study perspective, reflecting the selected reference frame. Although one study perspective was aligned with the slope and the other was aligned with the room axis, neither cue alone determined reference frame selection. These results parallel findings from other studies that placed multiple environmental cues in conflict (Kelly & McNamara, 2008; Shelton & McNamara, 2001). In those studies, reference frame selection occurred from the initial study perspective, regardless of study-perspective order. The present results indicate that slope exerts no more influence than does room shape during reference frame selection. Instead, reference frame selection was determined by the initial study perspective.

The results of Experiment 2 diverge from those of previous research in which pigeons preferentially used environmental slant to find a remembered location, even when enclosure shape provided a more reliable cue (Nardi et al. 2010). It is possible that humans and other animals weight environmental cues differently, but myriad differences between the two studies make it impossible to draw clear conclusions. Some of these differences include the type of task (spatial memory vs. spatial orientation), the implementation of the slant cue (slanted table vs. slanted floor), and the sensory signals indicating slant (vision only vs. vision plus proprioception).

General discussion

The primary purpose of this project was to evaluate the influence of environmental slant on spatial memory organization. Previous research indicates that environmental slant allows for superior navigation within the remembered environment (Restat et al., 2004). However, the beneficial effect of slant on navigation could be due to changes in the underlying structure of spatial memory or changes in spatial orientation in the presence of environmental slant. The usefulness of slant as a cue to spatial orientation has previously been established (Chai & Jacobs, 2010; Nardi et al. 2010, 2011). However, the influence of environmental slant on spatial memory organization has been relatively unexplored. Therefore, the present project was designed to investigate the role of environmental slant as a cue to reference frame selection when locations on a sloped surface are learned.

When environmental slant was the only environmental cue (Experiment 1), participants remembered object locations on a sloped table, using a reference frame aligned with the direction of the slope. As a result of this organization, subsequent perspective-taking performance was best when imagining perspectives aligned with the direction of slant. Furthermore, maps were drawn from a perspective parallel to the direction of slant. These results fit well with evidence that slope is incidentally encoded into spatial memory (Garling et al., 1990) and that slope influences the linguistic terms used for describing absolute spatial relationships (Brown & Levinson, 1993).

When environmental slant was placed in conflict with room shape (Experiment 2), reference frame selection occurred from the initial study perspective. This finding is consistent with Shelton and McNamara's (2001) theory that reference frame selection is based primarily on environmental cues aligned with the first study perspective; reference frame selection from the second study perspective occurs only when the second perspective offers better access to environmental cues. Determination of the relative influences of egocentric and environmental cues would require independent manipulation of those cues (e.g., Marchette & Shelton, 2010) and is beyond the scope of the present study.

The results of Experiment 2 are inconsistent with research showing that pigeons preferentially rely on environmental slant even when environmental shape is more predictive of location (Nardi et al., 2010). However, there are numerous differences between those experiments (beyond obvious differences between species). Spatial memory and spatial orientation tasks differ fundamentally, each with unique goals and relevant cues. Furthermore, environmental slant was conveyed visually in the present experiments, whereas past work used real ground planes that could be sensed visually and proprioceptively. Cue presentation across multiple senses could increase the salience of slant beyond that of room shape. Lastly, well-documented misperception of depth in VR (Loomis & Knapp, 2003) could have reduced the salience of slope in the present study.

The environments in the present experiments can be described as vista spaces, since the entire environment was visible from a single vantage point (Montello, 1993). In contrast, naturally occurring environmental slant often characterizes larger environments composed of numerous smaller vista spaces (e.g., locations on a hillside), so the same globally aligned slant can pervade multiple adjacent vista spaces. This description characterizes the virtual town used by Restat et al. (2004), in which the slant orientation was consistent throughout the town. The presence of a globally aligned slant across a large region might cause spatial memories of the component vista spaces to be organized around the same globally aligned reference frame. Such globally aligned reference frames could allow for easier cross-layout judgments (Kelly & McNamara, 2010), which were a necessary component of the pointing and navigation tasks used by Restat et al. Therefore, the improved navigation and pointing performance reported in those studies are probably due to multiple facilitative effects of environmental slant: Slant enables more accurate spatial orientation and might also enable more accurate cross-region judgments of location.

In sum, the present experiments establish a role for environmental slant in determining the reference frame structure of spatial memories. In the absence of other environmental cues, environmental slant leads to selection of a reference frame aligned with the direction of the slant. The role of environmental slant in reference frame selection is similar to the role of other environmental cues, such that incongruent environmental structures result in reference frame selection from the first study perspective.

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