Journal of Experimental Psychology:
Learning, Memory, and Cognition
2013, Vol. 39, No. 5, 1520–1537

0278-7393/13/$12.00 DOI: 10.1037/a0032382

Active and Passive Spatial Learning in Human Navigation: Acquisition of Survey Knowledge

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It seems intuitively obvious that active exploration of a new environment would lead to better spatial learning than would passive visual exposure. It is unclear, however, which components of active learning contribute to spatial knowledge, and previous literature is decidedly mixed. This experiment tests the contributions of 4 components to metric survey knowledge: visual, vestibular, and podokinetic information and cognitive decision making. In the learning phase, 6 groups of participants learned the locations of 8 objects in a virtual hedge maze by (a) walking, (b) being pushed in a wheelchair, or (c) watching a video, crossed with (1) making decisions about their path or (2) being guided through the maze. In the test phase, survey knowledge was assessed by having participants walk a novel shortcut from a starting object to the remembered location of a test object, with the maze removed. Performance was slightly better than chance in the passive video condition. The addition of vestibular information did not improve performance in the wheelchair condition, but the addition of podokinetic information significantly improved angular accuracy in the walking condition. In contrast, there was no effect of decision making in any condition. The results indicate that visual and podokinetic information significantly contribute to survey knowledge, whereas vestibular information and decision making do not. We conclude that podokinetic information is the primary component of active learning for the acquisition of metric survey knowledge.

Keywords: navigation, spatial cognition, proprioception, vestibular, decision making

It seems intuitively obvious that, when arriving in a new city, one learns more about the spatial layout of the city from actively walking around than from passively riding in a taxi. Despite this observation, research comparing active and passive spatial learning has yielded surprisingly mixed results (see Chrastil & Warren, 2012a, for a review). One reason for this inconsistency is that the active/passive dichotomy is too coarse a distinction: "Active" learning may involve multiple perceptual and cognitive components, which are often confounded in experimental designs. Moreover, these components might differentially influence the acquisition of different forms of spatial knowledge, which must also be distinguished experimentally. In this article we investigate four potential contributors to the acquisition of survey knowledge; planned companion articles will report on their contributions to graph knowledge (Chrastil & Warren, 2012b) and on the role of active attention in spatial learning (Chrastil & Warren, 2012c).

This article was published Online First April 8, 2013.

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Portions of this paper were included as part of Elizabeth R. Chrastil's doctoral dissertation. This research was supported by National Science Foundation awards BCS-0214383 and BCS-0843940. We would also like to thank Joost de Nijs, Michael Fitzgerald, Henry Harrison, Kurt Spindler, and members of the VENLab for assistance with the research and David Badre, Rebecca Burwell, and Mike Tarr for their helpful comments.

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Components of Active Learning

First, consider possible components of passive and active learning as one explores a new environment. Passive learning is presumably based solely on visual information about the environmental layout and path of self-motion, including optic flow, binocular disparity, and surface texture. Passive viewing involves only exposure to such visual information. In addition, we can identify six distinct components that might contribute to active learning during exploration: (a) efferent motor commands that determine the path of locomotion, (b) proprioceptive information about displacement with respect to the substrate (a and b together are known as *podokinetic information*; Weber, Fletcher, Gordon, Melvill Jones, & Block, 1998), (c) vestibular information about head movement in an inertial frame (a–c are collectively referred to as *idiothetic information*; Mittelstaedt & Mittelstaedt, 2001), (d) cognitive decision making about the direction of travel or the selected route, (e) the allocation of attention to relevant spatial properties of the environment, and (f) mental manipulation of spatial information (Chrastil & Warren, 2012a). Here, we examine the contributions of passive viewing and three potential active components—podokinetic information (motor and proprioceptive components are difficult to dissociate in walking), vestibular information, and decision making—with the aim of identifying which of them actually play a role in spatial learning.

Second, consider the forms of spatial knowledge that appear to underlie human navigation. Successful navigation between known locations might involve place recognition, reliance on beacons or landmarks, knowledge of routes or paths between places, and/or survey knowledge of their spatial layout (Siegel & White, 1975;

Trullier, Wiener, Berthoz, & Meyer, 1997; Wiener, Buchner, & Holscher, 2009): (a) *Beacons* and *landmarks* are salient features of the environment that act as place markers (beacons) or form a configuration that specifies a location (landmarks). (b) *Route knowledge* consists of a set of place–action associations, a specific sequence of turns at identifiable locations or decision points. (c) *Graph knowledge* consists of a network of places connected by paths, allowing for multiple paths to intersect at one location and enabling detours. A purely topological graph is a set of nodes (places) linked by edges (paths), whereas a labeled graph incorporates some coarse distance and direction information that may allow for approximate shortcuts. (d) *Survey knowledge* is configural "maplike" knowledge that includes metric distances and directions between locations. *Local* survey knowledge is based on a set of landmarks that are all visible from most places in the environment, whereas *global* survey knowledge must be constructed from subsets of landmarks visible from different locations (Benhamou, 2010). Global survey knowledge is akin to a Euclidean cognitive map or global metric embedding (Thrun, 2008), and it enables novel shortcuts between known locations that are out of view. A person possessing global survey knowledge knows not only the spatial relation between two places but also where those places are located within the larger environment. However, human global survey knowledge, as revealed by novel shortcuts, is often inaccurate and highly variable. Our purpose in the present experiment is to determine which aspects of active exploration contribute to global survey knowledge.

On the basis of theoretical considerations, one would expect the components of active learning to differentially affect the aspects of spatial structure that are acquired. Our first hypothesis is that idiothetic information should play a significant role in the acquisition of survey knowledge. Survey knowledge depends upon metric information about the distances traveled and angles turned during locomotion, such as that provided by the podokinetic and vestibular systems (see Israel & Warren, 2005, for a review). Although vision also provides information about the distances and directions of objects, visual space perception is subject to significant affine distortions (Koenderink, van Doorn, & Lappin, 2000; Loomis, DaSilva, Fujita, & Fukusima, 1992; Norman, Crabtree, Clayton, & Norman, 2005). The idiothetic systems specifically register metric information along a traversed path, which together with path integration could provide a basis for building up maplike survey knowledge (Gallistel, 1990; McNaughton, Battaglia, Jensen, Moser, & Moser, 2006).

Conversely, our second hypothesis is that active decision making about one's path of travel during exploration should contribute to the acquisition of route and graph knowledge, but it is less likely to contribute to survey knowledge. Given that route knowledge is believed to consist of a sequence of nominal left/right turns at recognized locations, making decisions about one's travel direction should facilitate the formation of such place–action associations. Similarly, given that graph knowledge consists of paths connecting places, making decisions about one's travel path should help build up such a graph. There may also be a role for decision making in the acquisition of survey knowledge that is related to prediction. When making travel decisions, the navigator could generate predictions about the outcome of the decision based on a forward model of the action and then compare the expected and actual outcomes; monitoring the prediction error could lead to improvements in the model and in subsequent self-motion estimation (Wolpert & Ghahramani, 2000). For example, predictions about the distance and direction between locations might be compared with the resulting idiothetic information, leading to improved survey knowledge; analogously, expectations about which path leads to a particular object in the maze might improve graph knowledge. Structures within the medial temporal lobe have been implicated both in spatial navigation and in prospective memory, such that memory of previous events allows for better prediction of future events (Bar, 2007; Buckner, 2010; Schacter, Addis, & Buckner, 2007). Volitional control over exploration has been shown to enhance spatial memory for objects in a grid (Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011), but it is not known whether this finding translates to survey knowledge in spatial navigation.

Here, we test the hypothesis that decision making contributes to survey knowledge. We expect that active decision making alone will not be sufficient for improved survey knowledge, although there may be an interaction such that an effect of decision making may be observed in combination with full idiothetic information (i.e., during walking). The contribution of decision making to graph knowledge will be addressed in a subsequent report (Chrastil & Warren, 2012b).

Active and Passive Survey Learning

Most previous research on active and passive spatial learning has focused on the role of perceptual information in the acquisition of survey knowledge, although the results have been inconsistent. Some experiments suggest that idiothetic information significantly contributes to survey knowledge (Chance, Gaunet, Beall, & Loomis, 1998; Ruddle, Volkova, & Bülthoff, 2011; Waller & Greenauer, 2007; Waller, Loomis, & Haun, 2004), whereas others have found that it contributes little beyond vision alone (Mellet et al., 2010; Waller & Greenauer, 2007; Waller, Loomis, & Steck, 2003).

Information

Waller et al. (2004) found a significant contribution of idiothetic information to survey learning. They tested survey knowledge in people who walked a prescribed route in virtual reality (VR) while wearing a head-mounted display (HMD), watched a matched video in the HMD while sitting, or wore the HMD and watched a matched video that had been smoothed to remove jitter. After learning the route, participants were asked to make judgments of relative direction between different locations on the route. Participants who walked were more accurate than those in either of the video groups, suggesting that idiothetic information contributes to learning survey knowledge.

To break idiothetic information into its components, Waller and Greenauer (2007) isolated the contributions of podokinetic, vestibular, and visual information to spatial updating during path integration. One group of participants walked a specified route in a series of hallways (podokinetic + vestibular + visual); another group was pushed in a wheelchair (vestibular + visual), and a third group watched a video (visual). After they had traveled one time through a hallway, participants were asked to point and estimate distances between locations on the path. Waller and Greenauer found no differences in pointing errors between groups, except when the locations were separated by a large number of turns. In those cases the walking group had significantly lower errors than the wheelchair and video groups, indicating that the idiothetic contribution came from podokinetic, not vestibular, information (see also Waller et al., 2003). Mellet et al. (2010) also found no difference in pointing errors between participants who learned fairly simple hallways by walking and those who used a joystick in VR. These two experiments indicate that idiothetic information contributes little to survey learning on simple paths, such as *U*-shaped hallways. However, a significant podokinetic contribution is revealed by more complex paths with a sufficient number of turns.

Several experiments sought to distinguish idiothetic information about translation and body rotation during exploration. Chance et al. (1998) had participants walk prescribed paths in virtual mazes (visual + idiothetic), stand and steer using a joystick (visual), or use a joystick for translation but physically rotate by stepping in place (visual + idiothetic for rotation). Participants were instructed to keep track of target locations along the path and to point to these locations once they reached the end of the path. After repeated exposure to the environment, participants in the walking condition had lower absolute pointing errors than did those in the joystick-only condition, whereas those in the physical rotation condition did not differ significantly from either group. These results suggest that combined idiothetic information about both translation and rotation is important for learning object locations.

In a recent experiment, Ruddle et al. (2011) asked participants to search freely for four target objects in a virtual marketplace, which was laid out on a grid plan. They were then instructed to find each target object again and estimate the distances and directions to the other three targets. In a small (10 m × 7 m) environment, one group walked (visual + idiothetic), another used a joystick for translation but made physical rotations (visual + idiothetic for rotation), and a third group only used a joystick (visual). The walking group traveled less to find the target objects and was more accurate in its distance estimates than were the other two groups, suggesting that idiothetic information about both translation and rotation is integrated for survey learning. In a scaled-up version of the same environment (45 m × 25 m), participants walked on an omnidirectional treadmill (visual + idiothetic), walked on a linear treadmill while using a joystick for rotation (visual + idiothetic for translation), physically rotated while using a joystick for translation (visual + idiothetic for rotation), or only used a joystick (visual). In this case, the two treadmill conditions were more accurate than the other two conditions on both distance and direction estimates, but there was no difference between the physical rotation and joystick-only conditions. These results indicate that idiothetic information contributes to distance learning in a small-extent grid environment but to both distance and direction learning in a large-extent environment. When distances were great in the large environment, idiothetic information for translation played a significantly greater role than that for rotation; passive visual information may be sufficient to adequately specify rotation (see Israel & Warren, 2005). However, whereas Chance et al. (1998) guided participants during learning, Ruddle et al. (2011) allowed them to explore freely; hence, the stronger idiothetic effect could be a consequence of active decision making.

The findings also suggest that informational components may interact with the size and complexity of the environment, such that visual information may be sufficient for learning smaller and simpler environments, and idiothetic information contributes more in large or complex environments. Ruddle et al. (2011) found a greater advantage for walking over visual exploration in their large environment, and others (Chance et al., 1998; Waller & Greenauer, 2007) observed a similar effect on paths with multiple turns. In contrast, those who found no contribution of idiothetic information (Mellet et al., 2010; Waller & Greenauer, 2007) used fairly simple paths, such as *U*-shaped hallways. Visual information may be sufficient to learn the layout of such simple environments, whereas idiothetic path integration makes a measurable contribution over long distances or multiple turns.

Decision Making

In contrast to the role of information, the role of cognitive decision making in the acquisition of survey knowledge has not been studied systematically. One recent experiment on path integration showed that those who made decisions about their outbound path had no better performance in returning home than those who were led on an outbound path (Wan, Wang, & Crowell, 2010). However, the outbound paths in that experiment were very simple and might not reveal a contribution of decision making. In addition, path choice may play a different role in a homing task than in a spatial learning task, so the results may not be applicable here. On the other hand, Yamamoto (2012) found that a visual preview of the room aided perception of walked distances but only when participants walked by themselves following a guide rope rather than being led by an experimenter. This result suggests that some control over movement might aid in acquiring metric information. Similarly, Summers, Levey, and Wrigley (1981) found that, compared to movement controlled by an experimenter, prior knowledge and efferent information were important factors in distance reproduction.

All extant research on the effect of decision making on survey learning has been conducted in desktop VR, in the absence of idiothetic information (e.g., Péruch, Vercher, & Gauthier, 1995; Wilson, Foreman, Gillett, & Stanton, 1997). The results reveal no difference in pointing errors between participants who made decisions about exploration and those who did not, or they reveal a minor advantage for participants who did not make decisions but watched others control the exploration path using a keyboard (Wilson et al., 1997; Wilson & Péruch, 2002). Experiments that included idiothetic information either guided participants on a prescribed route (e.g., Chance et al., 1998; Waller et al., 2004) or allowed them to explore freely (e.g., Ruddle et al., 2011), but they did not control the decision-making factor. Thus, previous studies have not independently manipulated information and decision making, making it difficult to determine their effects on survey knowledge. It is possible, for example, that decision making influences survey learning only when idiothetic systems are concurrently providing metric information (Chrastil & Warren, 2012a).

Spatial Updating and Path Integration

Research on spatial updating may also prove informative about the passive and active components of spatial learning. Spatial updating refers to keeping track of the spatial relations among a small array of objects as one moves around them. Spatial updating is closely related to path integration, but the experimental paradigms have important differences, which may make a direct comparison difficult (Chrastil & Warren, 2012a). In spatial updating experiments the observer typically rotates about a small set of objects that are viewed simultaneously, so their spatial relationships are visually specified as opposed to being derived by path integrating between them. Nevertheless, given that spatial learning presumably depends on keeping track of object positions as one moves about, evidence from spatial updating as well as path integration may have implications for acquiring metric survey knowledge.

The literature suggests that spatial updating during physical self-motion is a fairly automatic process (Farrell & Robertson, 1998;Rieser, 1989; Rieser, Guth, & Hill, 1986), whereas imagining or ignoring self-motion appears to be an effortful process (Farrell & Thomson, 1998). It is unclear, however, whether visual information is sufficient for spatial updating and which idiothetic components significantly contribute. Féry, Magnac, and Israël (2004) found that vestibular information alone is insufficient but that some measure of efferent control over when observer rotations start and stop is important. In contrast, Wraga, Creem-Regehr, and Proffitt (2004) found that motor efference added little to spatial updating beyond the contributions of vestibular input, but the combination of vestibular and proprioceptive information leads to superior performance over visual information alone. Although vestibular and proprioceptive information provide an advantage, there is some evidence that vision alone might be sufficient for spatial updating but possibly only in environments that had previously been learned by walking (Riecke, Cunningham, & Bülthoff, 2007).

Although some research suggests that spatial updating is automatic, a number of studies have shown that learning a scene from one viewpoint and then making judgments about the scene from a novel viewpoint, either actual or imagined, impairs performance (e.g., Shelton & McNamara, 1997, 2001; Tarr, 1995). Orientation-specific spatial learning can also be acquired through idiothetic information alone (Yamamoto & Shelton, 2005). These results support the notion that people have a viewpoint-dependent representation of spatial configurations, such that they have better access to scene information in familiar orientations. Spatial updating could mitigate the limitations of view-dependent spatial knowledge. It is not clear whether reduced accuracy from a novel viewpoint is due to a change in the orientation of the objects or a change in orientation of the viewer (Simons & Wang, 1998). Research into this question has revealed that vestibular information appears to be sufficient for spatial updating, whereas neither cognitive control of nor podokinetic information about the magnitude of the viewpoint shift is essential (Simons & Wang, 1998; Waller, Montello, Richardson, & Hegarty, 2002; Wang & Simons, 1999). There have been, however, a few reports limiting the scope of these effects (Motes, Finlay, & Kozhevnikov, 2006; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Teramoto & Riecke, 2010).

Finally, the contributions of visual and idiothetic information have also been tested in studies of path integration (Harris, Jenkin, & Zikovitz, 2000; Kearns, Warren, Duchon, & Tarr, 2002; Loomis et al., 1993). It appears that motor, proprioceptive, and vestibular information all contribute to path integration, with visual information for self-motion playing a significant but lesser role (Allen, Kirasic, Rashotte, & Haun, 2004; Kearns, 2003; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Tcheang, Bülthoff, & Burgess, 2011).

In sum, previous studies of spatial learning have had fairly mixed results. In large or complex environments, podokinetic information appears to contribute to survey knowledge, but there is little evidence for a role of vestibular information. The spatial updating literature, in contrast, suggests that vestibular information may be important to updating, with somewhat lesser contributions from efferent control and proprioception, whereas the path integration literature implies that the podokinetic system plays an important role. It should also be noted that in most cases, visual information appears to be sufficient for some survey learning and spatial updating to occur. The contribution of decision making has not been sufficiently tested in previous literature; desktop VR has yielded mixed results, and there have been no studies examining the contribution of decision making in the presence of full idiothetic information.

The Present Study

There are thus several outstanding questions that the present study aimed to test. First, the role of information should be examined systematically within one paradigm, considering previous mixed results. Second, the role of decision making must be investigated further, given the inconsistent findings in desktop VR. Third, a controlled study of possible interactions between these two factors has never been performed. Thus, the present experiment crossed three levels of information with two levels of decision making during exploration of a virtual hedge maze, yielding six groups (see Table 1). Full visual + vestibular + podokinetic information was available in the walking condition, visual + vestibular information was presented in the wheelchair condition, and visual information alone was presented in the video condition. Note that visual information about environmental layout, self-

Table 1
Experimental Design

Information	Decision: Yes	Decision: No
Visual + vestibular + podokinetic	Free walk	Guided walk
Visual + vestibular	Free wheelchair	Guided wheelchair
Visual	Free video	Guided video

motion, and location—including optic flow, binocular disparity, and surface texture—was available in all conditions. These were crossed with the free condition, in which participants made decisions about where to go during exploration, and the guided condition, in which participants were led along paths matched to the free walking group. Thus, decision making was manipulated at all three levels of information. After learning the maze, participants took novel shortcuts between target objects. This task probed metric survey knowledge by testing whether participants know the distances and directions between learned locations.

Based on the theoretical background and previous findings, several predictions can be made. First, idiothetic information, particularly podokinetic information, should be a significant contributor to survey learning. Whereas visual perception of distance and direction is subject to large affine distortions, idiothetic information specifies the traversed distances and angles needed to build up metric survey knowledge. Thus, we expect that shortcut performance will be better in the walking condition than in the video condition; the wheelchair condition will provide evidence about the specific role of vestibular information.

Second, the predicted contribution of decision making during exploration is less clear. We expect that decision making will not contribute to survey knowledge because it does not provide additional metric information over and above visual information alone, consistent with previous results in desktop VR. On the other hand, it remains possible that decision making might facilitate the acquisition of metric relations from idiothetic information, perhaps via predictions based on a forward model. Thus, decision making and information may interact, yielding better shortcut performance in the free walking than the guided walking condition but no difference between the free video and guided video groups. Decision making may also influence the deployment of attention, but this issue is examined in a future article (Chrastil & Warren, 2012c); in the present experiment, attention was unconstrained in all conditions.

Finally, note that the size and complexity of the environment may be important factors in revealing the role of idiothetic information or decision making. The medium-scale environment (11 m × 12 m) used here was larger than in most previous studies but smaller than in the large-scale environments used by Ruddle et al. (2011) and Waller et al. (2004), which were on the scale of city blocks. However, the internal structure of our hedge maze was fairly complex, with many acute and obtuse turns and path segments between objects, and hence required multileg path integration and numerous decision points. This complexity should be sufficient to reveal the contributions of idiothetic information and decision making during exploration.

The results demonstrate that visual and podokinetic information significantly contribute to survey knowledge, whereas vestibular information and decision making do not. Participants who walked during exploration had the greatest angular accuracy in their shortcuts, whereas those who rode in a wheelchair did not differ from those who watched a video. Moreover, making decisions during exploration made no contribution to survey learning. We conclude that podokinetic information is the primary component of active learning for metric survey knowledge.

Method

Participants

Participants included 134 (67 female) volunteers who were paid for their time. A total of 112 participants (56 female), with a mean age of 21.63 years (*SD* = 4.11), completed the experiment. Fifteen participants (9 female) withdrew due to symptoms of simulator sickness, and 7 participants (2 female) failed to find all of the objects during exploration and were excluded. The dropout rates due to simulator sickness (and failure to find all objects) for the different groups were as follows: free walk, 5 (1); guided walk, 1 (0); free wheelchair, 0 (4); guided wheelchair, 1 (0); free video, 8 (2); guided video, 0 (0). All participants read and signed a form indicating their consent to participate in the experiment, in accordance with a protocol approved by the Brown University Institutional Review Board.

Equipment

The experiment was conducted in the Virtual Environment Navigation Lab (VENLab), a 12 m × 14 m ambulatory virtual reality facility at Brown University. Images were presented to the participants in a Rockwell-Collins SR80A (Cedar Rapids, IA) head-mounted display (HMD) (63° height × 53° vertical field of view, 1,280 × 1,024 pixels, 60 Hz frame rate). Head position and orientation were recorded with an InterSense IS900 (Billerica, MA) tracking system (50 ms latency, 60 Hz sampling rate, 1.5 mm root mean square [RMS] and 0.1° RMS accuracy). Participants responded by walking to target locations and pressing a button on a radio mouse. Images were generated on a Dell XPS graphics PC (Round Rock, TX) with Vizard software (WorldViz, Santa Barbara, CA) to render the images. Naturalistic evening sounds were presented over headphones to interfere with any auditory location or orientation cues.

Displays

The 11 m × 12 m virtual maze environment (see Figure 1) contained eight objects located at the ends of branch hallways, so they were not visible from the main corridors. They were models of common objects, such as a sink or bookcase, scaled to be easily visible at eye height. In addition, four landmarks—familiar paintings by Monet, Dali, Magritte, van Gogh—each appeared in a constant location on the walls of the main corridors to aid orientation. The ground in each corridor was a random grayscale gravel texture with a brown and green border. On test trials, the maze was replaced with a circular 750-m-radius ground plane containing only a random grayscale Voronoi texture.

Design

Six groups of participants were tested in a 3 × 2 design, with three levels of information (walk, wheelchair, video) crossed with two levels of decision making (free, guided), yielding six exploration conditions (see Table 1): (a) free walking, (b) guided walking, (c) free wheelchair, (d) guided wheelchair, (e) free video, and (f) guided video. Each group contained 16 randomly assigned participants, with the restriction that the groups were evenly di-

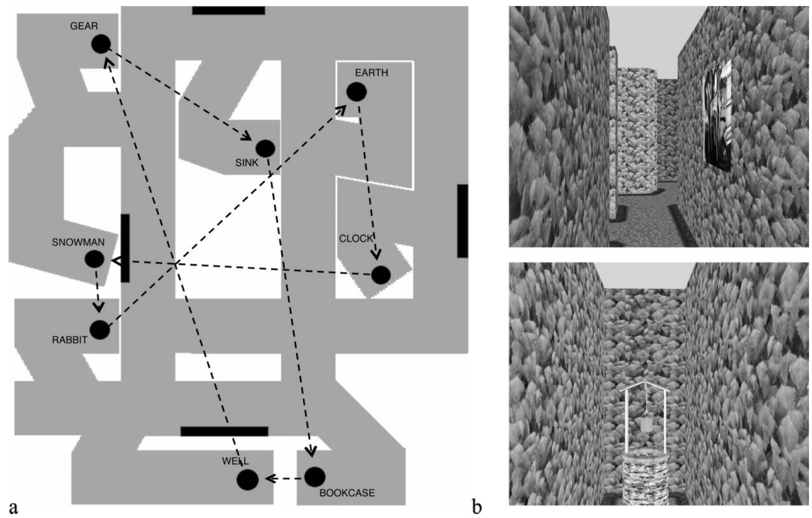

Figure 1. (a) Outline of the maze used in this experiment. The maze included eight objects (black circles) and four landmarks (paintings, black rectangles). The eight shortcuts (trial types) are indicated by dashed arrows. Participants never saw this overhead view of the maze. (b) Views from inside the maze, from the participant's perspective. Top: View of one of the hallways, including a painting. Bottom: View of one of the objects in the maze, the well.

vided between men and women, making 96 participants in the initial experiment. Eight additional participants were tested in two of the groups (free walking and free video), for a total of 112 participants.

Procedure

Participants were informed that they would be traveling through hallways in a virtual hedge maze and that the task was to find all of the objects and learn their locations. Participants in the video groups sat in an adjustable chair at approximately their measured standing height, and their virtual eye height was set to their measured standing eye height; eye height in the walking and wheelchair groups corresponded to their actual eye height as measured by the head tracker.

Practice. Participants were given several minutes in a practice maze in their assigned exploration condition. It had a different layout from the test maze and contained objects not used during the experiment. This allowed participants to become familiar with virtual reality and to practice with a tablet PC (free wheelchair condition) or a keyboard (free video condition) as an interface.

Learning phase. In the learning phase, participants were informed they would explore the environment for 10 minutes. They were guided to one of six start locations, and the experimental maze appeared. (a) In free walking, participants were instructed to explore the virtual environment by walking freely. This provided them with normal visual, vestibular, and podokinetic information as well as decision making. (b) In guided walking, participants were guided by the arm along the same paths as the free walking group. This gave them matched visual and idiothetic information without the decision-making component. (c) In free wheelchair, participants were pushed through the maze in a wheelchair by a walking experimenter. They indicated which direction they wanted to turn by pressing buttons on a tablet PC, which then played a turn instruction to the experimenter through headphones. This minimized podokinetic information but retained some vestibular information. (d) In guided wheelchair, participants were pushed through the maze, on paths matched to those for the free walking group, without decision making. (e) In free video, seated participants pressed buttons on a keyboard to turn while exploring the environment, analogous to desktop VR. This left only visual information, including optic flow, disparity, and surface texture, presented in the HMD. (f) In guided video, participants viewed the exploration video from the free walking group in the HMD, without making decisions.

Given that the experiment was designed to test the effect of removing active components from normal walking, the paths in all guided conditions were matched to those in the free walking group. The paths in the free wheelchair and free video groups could not be matched to free walking, but the speeds for these groups were matched to the mean free walking speed. Exploration paths were analyzed to check for significant differences between conditions (see Dependent Measures).

Test phase. Survey knowledge was tested with a novel shortcut task in which the participant walked directly from a starting object to the remembered location of a target object (see Figure 1a). Prerecorded instructions were presented to the participants over the headphones and were repeated by the experimenter. Participants then completed two practice trials with object pairs not used during the test phase, followed by 40 test trials. To begin each trial, the participant was wheeled to the entrance of the branch hallway containing the starting object (approximately 1 meter from the object); then, the participant clicked the mouse, whereupon the maze appeared. This allowed participants to orient themselves while preventing spatial learning during the test phase. The participant was instructed to walk to the starting object, at which point the maze walls, paths, and objects disappeared and were replaced by the Voronoi ground plane. The target object was then named over the headphones, the participant turned to face its remembered location, and clicked the radio mouse; this was taken as the *starting point* of the shortcut. They then walked forward until they thought they had reached the target's location and clicked the radio mouse again to end the trial; this was taken as the *stopping point* of the shortcut. Finally, the experimenter wheeled the participant through the ground plane environment to the starting location of the next trial, taking a circuitous route. Head position and orientation were recorded throughout the trial, with the locations of the two mouse clicks serving as endpoints for the shortcut.

Participants sometimes walked outside the tracking area when taking a shortcut, triggering the appearance of an emergency stop display (a virtual brick wall with a verbal "Stop!" command) so they would not walk into the laboratory wall. This occurred on 32% of test trials, with no differences between conditions. In such cases, the trial ended when the participant left the tracking area, and only data on initial direction, not final position, were included in the analysis.

There were eight object pairs or "trial types" in the test phase (see Figure 1a). Each participant received five trials for each trial type, for a total of 40 test trials. All trials were presented in a random order with the exception that trial types did not repeat back-to-back. Full visual, vestibular, and podokinetic information was present during the test phase. All groups must be tested under the same conditions to assess the effect of the learning, or else differences in performance could potentially be attributed to differences in the testing conditions.

Follow-up tests. Finally, participants performed several additional tests to probe their performance and assess their spatial abilities: (a) Sketch map, in which they were presented with a list of the names of the objects and paintings in the virtual maze and asked to draw freehand a map of the maze within a rectangle, using a pen on a sheet of paper. The maps were scored on a 1–10 scale by a double-blind rater for general accuracy of spatial layout (compare Figure 1a), with most importance given to the locations of the hallways and the relative positions of the objects and paintings. (b) Description of the strategies participants used during both the exploration and the test phases. (c) Santa Barbara Sense of Direction Scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). (d) Questionnaire about age, duration, and frequency of current and past video game use (including first-person navigational video games) and ratings of nausea and sense of immersion in the virtual world during the experiment. (e) Road Map Test (Money & Alexander, 1966; Zacks, Mires, Tversky, & Hazeltine, 2000), in which participants describe a predrawn route on a city map by saying "left" or "right" to indicate each turn without rotating the page, modified to have a 20-s time limit. (f) Perspective-Taking Test (Kozhevnikov & Hegarty, 2001), in which participants view an array of objects on a page and indicate their directions from different imagined viewpoints. These measures were collected as a precaution to evaluate whether the groups differed on aspects of spatial ability. Equal numbers of men and women were tested in each group to avoid confounding by documented sex differences (e.g., Moffat, Hampson, & Hatzipantelis, 1998; Waller, 2000; Wolbers & Hegarty, 2010). Video game ability has also been shown to be a factor in virtual navigation (Richardson, Powers, & Bousquet, 2011). The Road Map Test and the Perspective-Taking Test gauge a navigator's ability to process location and direction information from different perspectives, which could be important for acquiring survey knowledge during exploration or for orienting within the maze during the test phase.

Dependent Measures and Analysis

Multiple dependent measures were taken for each trial, but many of them were redundant and yielded very similar results. For ease of understanding, only the primary angular and distance measures are reported here.

1. *Initial angular error* is the difference between the actual target direction and the initial walking direction when the participant left the starting object. Initial walking direction is the unit vector from the head position at the starting point to the head position 1 m away. The initial angular error is the difference between this vector and the correct unit vector toward the actual target location. If the participant traveled less than 1 meter during the trial (e.g., if he or she thought the target was very close), the head position at the stopping point was used to determine the walking direction. The accuracy of this directional response was estimated in two ways. First, using linear measures, we computed the absolute angular error (AE) in each condition as the mean of the unsigned angular error of all trials for each participant. Chance performance corresponds to an AE of 90°, as follows: If a participant is truly disoriented, his or her responses will be randomly distributed over ±180° from the target direction; the absolute value of that distribution has a range of 180°, with a mean of 90°. Second, using circular measures, we computed the angular constant error (CE) for each trial type in each condition as the circular mean of the signed angular error, where positive values indicate errors to the left of 0 on the circle and negative values indicate errors to the right of 0 on the circle. Measures of variability (variable error, or VE, the standard deviation of absolute error) showed a pattern of results similar to that of accuracy and are not reported.

2. *Path length* is the linear distance from the starting point to the stopping point of the shortcut. *Path length error* is the signed difference between the path length and the actual distance from the starting object to the target object, where a positive value indicates an overshoot and a negative value indicates an undershoot. Because path length data from trials in which the participant left the tracking area were not included in the analysis, mean path lengths were underestimated. In addition, final angular error, final position error, and response times were also measured but yielded similar results.

3. Measures of exploration during the 10-min learning phase included the *total distance traveled*, the *total angular rotation*, and the mean *number of visits per object*; the standard deviation (*SD*) and range of the number of visits both reflect how evenly a participant explored the environment.

Analysis was performed with MatLab (MathWorks), SPSS (IBM), and Oriana (Kovach Computing Services) software. We faced two problems in our analysis of angular error: Although angular variables call for circular statistics (Batschelet, 1981), the available factorial analyses are limited. In addition, because dif-

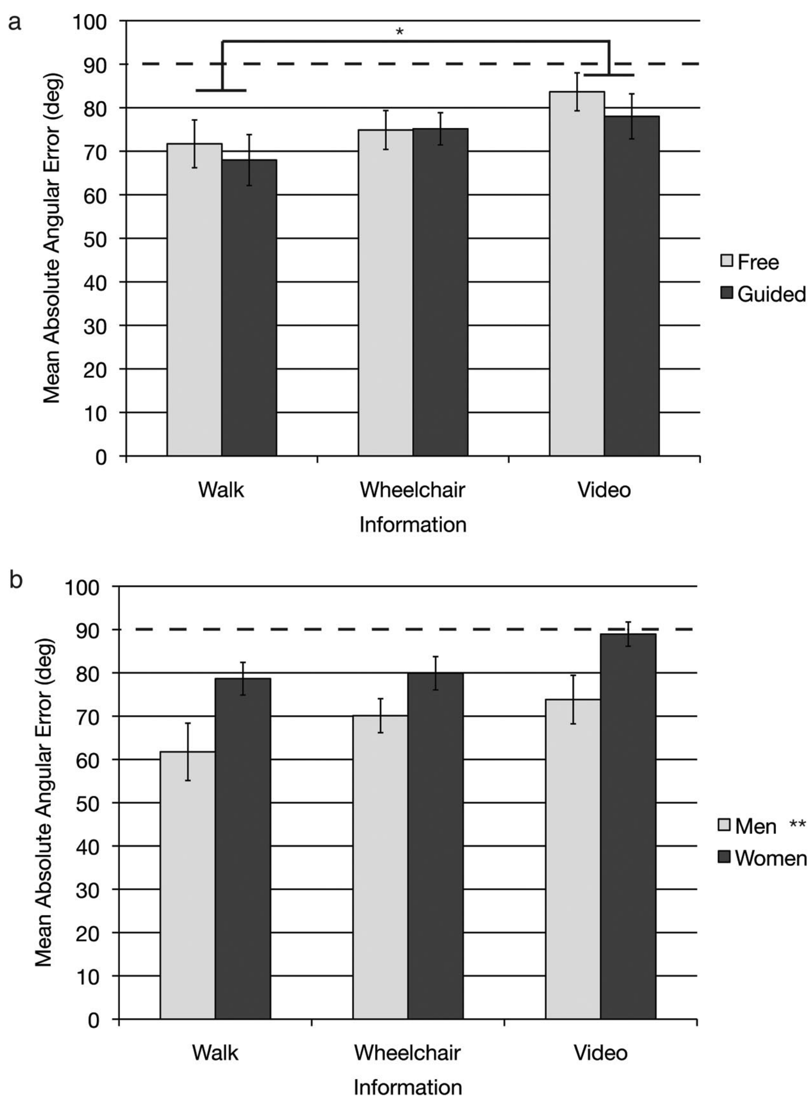

Figure 2. Absolute angular error on shortcuts. (a) Mean AE in the six exploration conditions, collapsed over sex. (b) Mean AE broken down by sex, collapsed over the decision-making factor. Chance performance is indicated by a dashed line at 90 degrees (deg); $N = 112$; error bars indicate between-subject standard error. AE = absolute error. $^{*}p < .05$. $^{**}p < .01$.

ferent trial types demanded different turn magnitudes, averaging error over trial types mixes large and small errors, exaggerating the variance. Consequently, we decided to perform two separate analyses of initial angular error. First, we performed a linear analysis on AE across trial types, based on the mean absolute error (AE) of all 40 trials for each participant. This effectively removed the circularity of the data by collapsing the range to 0 to 180°—allowing for more sophisticated statistical techniques—and averaged over trial types. These variables were analyzed with a normal $3 \times 2 \times 2$ (Information × Decisions × Sex) analysis of variance (ANOVA). Second, we performed a circular analysis on CE separately for each trial type, based on the mean constant error (CE) of 5 trials for each participant. The CE was analyzed with Watson–Williams one-way ANOVAs for circular data, and the VE was analyzed with a linear $8 \times 3 \times 2 \times 2$ ANOVA, with trial type as a repeated measure and information, decision making, and sex as between-subjects factors.

Preliminary analysis. A preliminary analysis was performed on data from 16 participants per group. There were no signs of a decision-making effect on angular AE ($F_{1,\ 94} = 0.005$, $p = .943$, $\eta_p^2 = 0.000$), but there were marginal effects of information ($F_{2,\ 93} = 1.754$, $p = .179$, $\eta_p^2 = 0.040$). In particular, a Helmert contrast showed a marginal difference in AE between the walking condition and the mean of the wheelchair and video conditions ($p = .073$). An analysis of effect size revealed that the main effect of information stabilized around a moderate value of $\eta_p^2 = 0.05$ with a group size of $N = 12$, whereas the effect size of decision making remained near zero. Given the large interindividual variability (see Figure 3), this result justified an increase in power to further investigate the

Table 2
Mean Absolute Angular Errors (AEs), by Trial Type

Trial type	Free walking	Guided walking	Free wheelchair	Guided wheelchair	Free video	Guided video
Sink to bookcase	85.6°	75.8°	65.1°	96.9°	91.6°	105.4°
Well to gear	35.3°	39.4°	45.3°	30.6°	57.0°	38.2°
Gear to sink	48.3°	59.6°	61.7°	63.7°	83.0°	69.5°
Clock to snowman	76.9°	75.7°	73.9°	67.3°	70.9°	81.0°
Earth to clock	85.8°	69.8°	93.3°	74.9°	63.8°	69.3°
Rabbit to earth	66.5°	76.5°	83.2°	88.6°	104.4°	93.3°
Snowman to rabbit	109.0°	87.8°	106.8°	122.4°	105.1°	102.8°
Bookcase to well	62.1°	59.0°	68.8°	57.5°	94.8°	63.5°

information contrast by adding eight participants to the free walking and free video groups. Thus, the final analyses included ANOVAs for unequal *N* on data from 24 participants in the two free groups and 16 participants in each of the other groups, for a total of 112 participants.

Results

Shortcut Direction

Absolute angular error (AE). The mean absolute angular error (unsigned error) in each condition appears in Figure 2a (and is broken down by trial type in Table 2). One-sample *t* tests revealed that the AE was significantly better than chance performance (90°) in five of the six conditions, including free walking ($t_{23} = -3.337$, $p = .003$), guided walking ($t_{15} = -3.762$, $p = .002$), free wheelchair ($t_{15} = -3.395$, $p = .004$), guided wheelchair ($t_{15} = -4.012$, $p = .001$), and guided video ($t_{15} = -2.318$, $p = .035$). Only the free video condition ($t_{23} = -1.458$, $p = .158$) was not significant; however, subsequent analysis revealed that the signed CE was statistically different from chance (see below). Although the errors are fairly high, it appears that some survey learning occurred in all conditions.

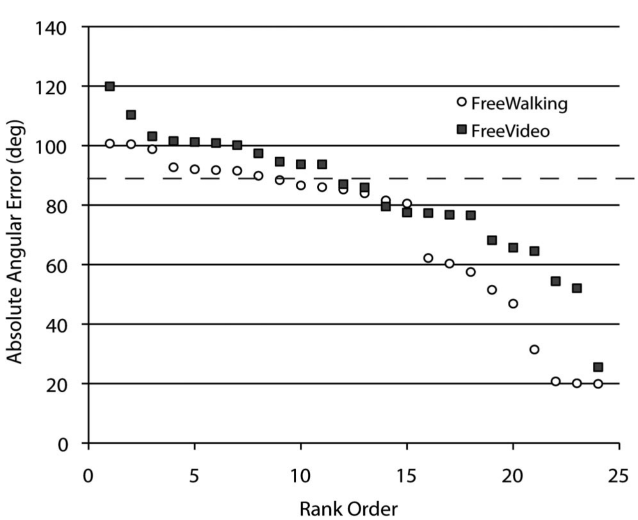

Figure 3. Individual performance in the free walking and free video conditions. Rank order of mean absolute error (AE). Chance is indicated by the dashed line at 90 degrees (deg).

Shortcut directions were most accurate in the walking condition, as estimated by the absolute angular error. A three-way ANOVA for unequal *N* (3 information × 2 decision × 2 sex) on the mean AE found a marginal main effect of information ($F_{2, 109} = 2.708$, $p = .072$, $\eta_p^2 = 0.051$). Post hoc Tukey tests revealed that the walking condition had significantly lower errors than the video condition ($p = .046$). Together these results imply that podokinetic information provides an advantage over vision alone for survey learning, whereas vestibular information does not. In contrast, there was no effect of decision making ($F_{1, 110} = 0.580$, $p = .448$, $\eta_p^2 = 0.006$) and no interactions. There was, however, a main effect of sex ($F_{1, 110} = 12.033$, $p = .001$, $\eta_p^2 = 0.107$), such that men had significantly lower AE than did women (see Figure 2b).

Figure 3 represents the pattern of individual accuracy and precision in the free walking and free video groups (each $N = 24$). Participants are plotted in rank order by performance, from left to right. Examination of the absolute angular error indicates that 22 out of 24 members of the free walking group have a lower AE than does their peer in the free video group ($p < .0001$ by a two-tailed sign test). Marked differences occur in the top third of the distribution, and the bottom half is at or below chance performance (AE = 90°).

Constant angular error (CE). The CE (signed error) also demonstrated that shortcut directions were above chance. A circular Rayleigh test was performed on all trials for each of the six conditions. The results confirmed that all conditions were significantly different from chance (all *p*s < .001); that is, the CEs were not randomly distributed around the circle but tended to cluster. When this analysis was repeated for each trial type, the results were similar: CEs were significantly different from chance on 43 out of 48 Rayleigh tests. This result implies that passive vision alone was sufficient for some survey learning.

The mean CE in each condition, broken down by trial type, appears in Figures 4 and 5. A set of one-way Watson–Williams tests, one for each of the eight trial types, was used to analyze the main effect of information, and a second set was used to analyze the main effect of decision making; the Bonferroni correction was applied for two comparisons made on the same data. The results appear in Table 3. First, consider the main effect of information (see Figure 4). Of the eight trial types, four of the Watson–Williams tests were significant and two more were marginally significant. Moreover, the mean CE was closer to 0 in the walking condition than the video condition for seven of the eight trial types ($p = .025$, Wilcoxon signed rank tests) and was closer to 0 in the walking condition than the wheelchair condition for all eight trial

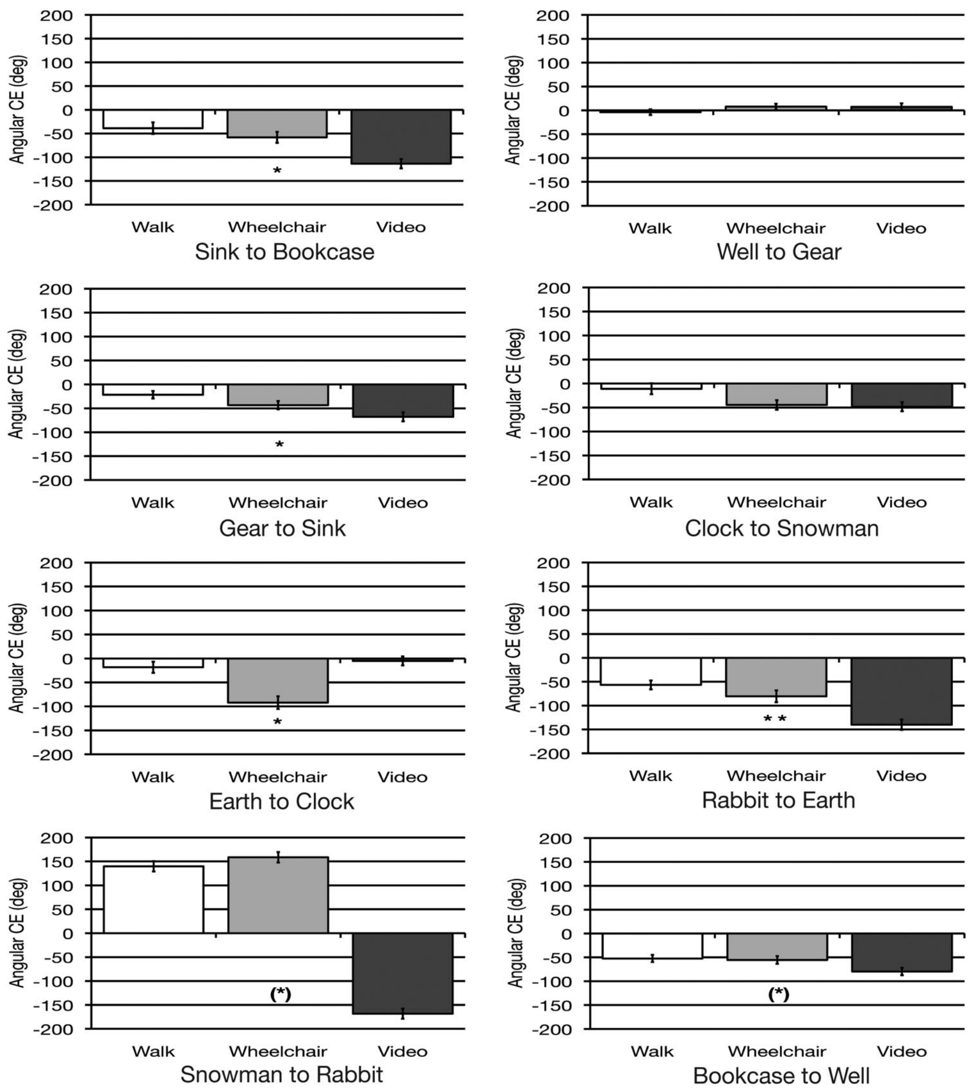

Figure 4. Angular constant error (CE) in each information condition for the eight trial types, collapsed over decision-making conditions. Each graph depicts the mean CE computed on the five trials for each trial type per participant; error bars indicate between-subject standard error. Significant main effects of information are indicated with asterisks. deg = degrees. * $p < .05$. ** $p < .01$.

types (p = .012). This finding confirms that the podokinetic advantage generalizes across target objects with different directions and distances. In contrast, for the main effect of decision making (see Figure 5), none of the eight Watson–Williams tests yielded a significant difference between the free and guided conditions for any trial type.

Path Length

Mean path length for each trial type is represented as a function of actual target distance in Figure 6. We performed a mixed four-way ANOVA on path length, with trial type as a within-subject factor and information, decision making, and sex as between-subjects factors. This analysis yielded a main effect of trial type ($F_{7,\ 105} = 20.509$, $p < .001$, $\eta_p^2 = 0.170$), indicating that participants distinguished targets at different distances, and a main effect of information ($F_{2,\ 109} = 3.393$, $p = .038$, $\eta_p^2 = 0.064$), but no main effect of decision making and no trial type by information interaction. Post hoc Tukey tests revealed that the walking condition had significantly longer paths than the video condition (p = .024). Thus, the walking group traveled farther than the video groups but appeared to be no more accurate (slope was not significantly closer to the diagonal in Figure 6a). There was also a main effect of sex ($F_{1,\ 110} = 7.750$, $p = .006$, $\eta_p^2 = 0.072$), such that men traveled farther than women.

The accuracy of shortcut distance was estimated by the constant path length error (signed error) for each trial type, which corresponds to the vertical distance from the diagonal in Figure 6. A similar four-way ANOVA on path length error yielded a main effect of trial type ($F_{7,\ 105} = 477.209$, $p < .001$, $\eta_p^2 = 0.827$),

Table 3
Results of Tests on Constant Angular Error (CE), by Trial Type

Trial type	Information[a]		Decision making[b]	
	F	p	F	p
Sink to bookcase	4.906	0.013*	0.434	0.513
Well to gear	0.861	0.431	1.695	0.198
Gear to sink	4.878	0.013*	0.040	0.842
Clock to snowman	1.605	0.215	0.050	0.823
Earth to clock	4.583	0.017*	0.091	0.765
Rabbit to earth	8.214	0.001**	0.010	0.921
Snowman to rabbit	2.832	0.072	0.227	0.636
Bookcase to well	2.892	0.0686	1.672	0.201

[a] Watson–Williams tests comparing the three levels of information (combining free and guided). [b] Watson–Williams tests comparing two levels of decision making (combining walk, wheelchair, and video).
* $p < .05$. ** $p < .01$.

reflecting the fact that participants tended to overshoot the two shortest distances and undershoot the longer distances. There was also a main effect of information ($F_{2,\ 109} = 3.571$, $p = .032$, $\eta_p^2 = 0.067$): The walking condition had lower path length error than did the video condition ($p = .020$, Tukey test). However, this effect is a consequence of the fact that the walking group had significantly longer paths than the other groups; there is no evidence that its shortcuts were actually more accurate, for the slope in Figure 6a is no closer to the diagonal. In addition, there was no main effect of decision making ($F_{1,\ 110} = 0.062$, $p < .803$, $\eta_p^2 = 0.001$). Finally, there was a significant effect of sex ($F_{1,\ 110} = 7.522$, $p = .007$, $\eta_p^2 = 0.070$) and a Trial Type × Sex interaction ($F_{7,\ 105} = 4.504$, $p < .001$, $\eta_p^2 = 0.043$).

In sum, it appears that active exploration made little contribution to the accuracy or precision of shortcut distances.

Sketch Maps

Sample sketch maps appear in Figure 7, and the mean scores in each condition are plotted in Figure 8. A three-way ANOVA found a main effect of decision making ($F_{1,\ 110} = 5.630$, $p = .020$, $\eta_p^2 = 0.053$), such that participants in the guided condition actually drew better maps overall. There was no main effect of information ($F_{2,\ 109} = 1.449$, $p = .240$, $\eta_p^2 = 0.028$); however, there was an Information × Decision Making interaction ($F_{2,\ 106} = 8.051$, $p = .001$, $\eta_p^2 = 0.139$). Linear contrasts revealed a significant effect of information in the free condition ($F_{2,\ 62} = 6.744$, $p = .002$, $\eta_p^2 = 0.181$) but no such effect in the guided condition ($F_{2,\ 46} = 1.939$, $p = .156$, $\eta_p^2 = 0.079$). Post hoc Tukey tests also showed that the free walking group drew significantly better sketch maps than did the free wheelchair ($p = .049$) and free video ($p = .002$) groups, which were not different from each other ($p = .725$); there were no group differences in the guided condition. Thus, there appears to be a podokinetic advantage for map drawing only when participants make decisions during exploration. Note that the maps in the guided video condition were judged to be as good as those in the free walking condition; the lowest rated maps were in the free video condition. There was also a main effect of sex ($F_{1,\ 110} = 16.906$, $p < .001$, $\eta_p^2 = 0.145$), such that men drew better sketch maps than did women.

Group Differences

The group differences highlighted in Figure 3 warrant further consideration. Establishing that the experimental groups did not differ greatly on individual measures of spatial ability or experience in VR would support the attribution of the results to the experimental manipulations. More detailed analysis of individual differences and their relationship to shortcut performance is planned for a future article.

Spatial ability. To assess whether the random assignment of participants to experimental conditions yielded comparable spatial abilities in each group, three-way ANOVAs (3 information × 2 decisions × 2 sex) were performed on seven individual measures. For age, there was a significant Information × Sex interaction ($F_{2,\ 106} = 4.579$, $p = .013$, $\eta_p^2 = 0.084$). Men in the wheelchair condition tended to be somewhat older than those in the walk or video conditions, although the 12 group means had a fairly narrow range (19–25 years).

The spatial ability tests primarily revealed significant sex differences, with men tending to have better scores than did women. The only effect for the Santa Barbara Sense of Direction Scale was a sex difference ($F_{1,\ 110} = 5.622$, $p = .020$, $\eta_p^2 = 0.053$). The Perspective-Taking Test also showed a sex difference ($F_{1,\ 110} = 10.085$, $p = .002$, $\eta_p^2 = 0.092$) as well as an Information × Sex interaction ($F_{2,\ 106} = 3.376$, $p = .038$, $\eta_p^2 = 0.063$), such that women in the wheelchair group had better scores than did women in the video group, whereas men in the video group had better scores than did women in the walking or video groups. The Road Map Test also exhibited a significant sex difference ($F_{1,\ 110} = 10.080$, $p = .002$, $\eta_p^2 = 0.092$) and a decision-making effect ($F_{1,\ 110} = 5.738$, $p = .018$, $\eta_p^2 = 0.055$), such that the guided group had better scores than did the free group.

There were also significant sex differences in video game experience, with men using video games more often than did women. The frequency of current video game use showed a sex difference ($F_{1,\ 110} = 7.496$, $p = .007$, $\eta_p^2 = 0.070$), but also an effect of information ($F_{2,\ 109} = 3.425$, $p = .036$, $\eta_p^2 = 0.065$) and an Information × Decision Making interaction ($F_{2,\ 106} = 3.362$, $p = .039$, $\eta_p^2 = 0.064$). Post hoc Tukey tests found that participants in the video group played video games marginally more often than did those in the walking group ($p = .061$); the guided video group played marginally more often than the guided wheelchair group ($p = .057$). Similarly, past use of first-person navigational video games (but not current use) revealed a sex difference ($F_{1,\ 110} = 14.294$, $p < .001$, $\eta_p^2 = 0.125$) and an effect of information ($F_{2,\ 109} = 3.334$, $p = .040$, $\eta_p^2 = 0.063$), such that the video group had played significantly more often than the walking group ($p = .044$, Tukey test).

It is possible that the video group's slightly greater experience with video games facilitated its members' survey learning and, hence, reduced the effect of information, yet a significant podokinetic advantage was observed nevertheless. Otherwise, there were no consistent differences in spatial ability or video game experience between the experimental groups. The most prevalent difference in the spatial ability tests was the sex difference, and men also had more video game experience than did women. These factors might contribute to the main effects of sex observed in shortcut performance.

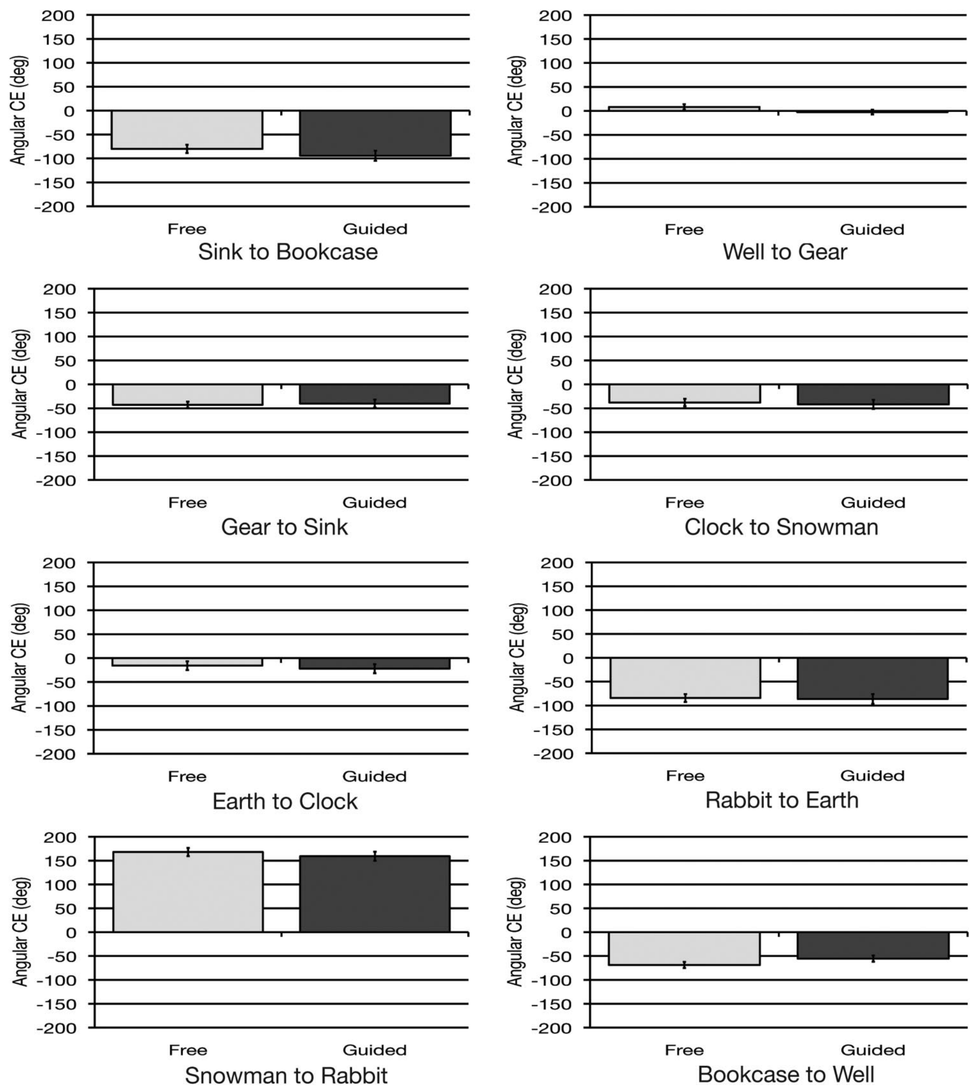

Figure 5. Angular constant error (CE) in the free and guided conditions for the eight trial types, collapsed over information conditions. Each graph depicts the mean CE computed on the five trials for each trial type per participant; error bars indicate between-subject standard error. None of the decision-making comparisons were significant. deg = degrees.

Experience in VR. To determine whether the experimental conditions were associated with different individual experiences during the experiment, three-way ANOVAs (3 information × 2 decisions × 2 sex) were performed on seven measures of experience.

There were significant differences in nausea ratings between the information groups ($F_{2,\ 109} = 7.526$, $p = .001$, $\eta_p^2 = 0.131$). Post hoc Tukey tests showed that the walking group experienced significantly less nausea than the video group ($p < .001$) and marginally less nausea than the wheelchair group ($p = .066$). Greater nausea ratings could imply that participants in the wheelchair and video groups were more distracted, possibly leading to lower performance. However, there were no group differences in ratings of immersion in the virtual environment.

For total distance traveled during exploration, there was a significant Information × Sex interaction ($F_{2,\ 106} = 3.993$, $p = .022$, $\eta_p^2 = 0.075$). Men in the video group tended to explore more, largely due to the free video condition with its familiar keyboard controller. Total angular rotation differed between information conditions ($F_{2,\ 109} = 9.020$, $p < .001$, $\eta_p^2 = 0.155$) and exhibited an Information × Decision Making interaction ($F_{2,\ 106} = 7.128$, $p = .001$, $\eta_p^2 = 0.127$). The wheelchair group ($M = 35523.1°$, $SD = 8481.7$) rotated significantly less than either the walking group ($M = 43840.1°$, $SD = 8292.3$; $p < .001$) or the video group ($M = 42645.3°$, $SD = 11354.9$; $p = .002$, Tukey tests). There was also a sex difference ($F_{1,\ 110} = 5.678$, $p = .019$, $\eta_p^2 = 0.055$), as women tended to rotate less than men, especially in the free video condition.

The mean number of visits per object during exploration differed between information conditions ($F_{2,\ 109} = 3.570$, $p = .032$, $\eta_p^2 = 0.067$), and there was an Information × Sex interaction ($F_{2,\ 106} = 5.433$, $p = .006$, $\eta_p^2 = 0.098$). The wheelchair group

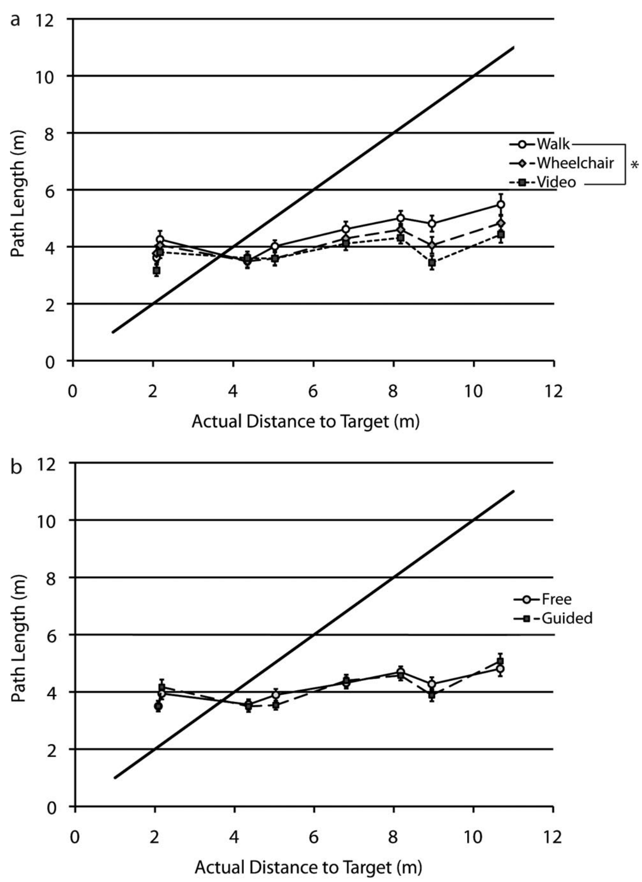

Figure 6. Mean path length for each of the eight trial types as a function of the actual distance to the target; error bars indicate between-subject standard error. (a) Path length for the three information conditions, collapsed over decision-making conditions. There was a significant effect of information on path length but no information by trial type interaction. (b) Path length for the free and guided conditions, collapsed over information conditions. None of the information comparisons were significant. * $p < .05$.

(M = 2.88, SD = 0.61) made significantly fewer visits per object than either the walking group (M = 3.23, SD = 0.59, p = .049) or the video group (M = 3.23, SD = 0.73, p = .047, Tukey tests). Men in the wheelchair group tended to make fewer visits than did men in the walking or video group, and women in the video group made fewer visits than did men in the video group. More important, the SD of the number of visits per object differed between information conditions ($F_{2,\ 109} = 4.274$, $p = .017$, $\eta_p^2 = 0.079$), such that the walking group (mean SD = 0.92) distributed visits across objects more evenly than did the video group (mean SD = 1.15; p = .001), which was marginally different from the wheelchair group (mean SD = 0.99; p = .055, Tukey tests).

In addition, the SD of visits per object differed between the decision-making conditions ($F_{1,\ 110} = 7.075$, $p = .009$, $\eta_p^2 = 0.066$), and it exhibited an Information × Decision Making interaction ($F_{2,\ 106} = 5.893$, $p = .004$, $\eta_p^2 = 0.105$) and an Information × Sex interaction ($F_{2,\ 106} = 4.194$, $p = .018$, $\eta_p^2 = 0.077$). Surprisingly, the guided group (mean SD = 0.94) visited objects more evenly overall than did the free exploration group (mean SD = 1.08). Given that guided paths were matched to free walking paths, this effect was actually driven by the fact that the free video group (mean SD = 1.292) visited objects less evenly than did the free walking group (mean SD = 0.888, p = .001, Tukey test). Men in the video groups tended to be more uneven with their visits than men in the walk or wheelchair groups, again, likely due to a difference between men in the free walking group (mean SD = 0.768) and the free video group (mean SD = 1.411). The range of the number of visits per object had a similar pattern of effects.

The main finding of the exploration analysis is that the free walking group tended to visit objects most evenly and the free video group did so least evenly, implying that idiothetic information helps participants keep track of the locations they have previously explored. However, it is unlikely that even exploration per se accounts for reduced error during the test phase, because error was similarly reduced in the guided walking group compared to the guided video group (see Figure 2a), even though their exploration paths were matched. Rather, this pattern of results suggests that podokinetic information about the relations between visited locations is the common mechanism behind both even exploration and improved survey learning. Secondarily, there was less total rotation and fewer visits in the wheelchair group, possibly due to the mechanics of the wheelchair.

Discussion

To investigate potential components of active and passive spatial learning, we tested the contributions of visual, vestibular, and podokinetic information and cognitive decision making to the acquisition of survey knowledge in a medium-scale virtual environment. Participants explored the environment by watching a video, being pushed in a wheelchair, or physically walking while either making decisions about where to explore or being guided, and they were then tested on a novel shortcut task. Performance was slightly above chance in the passive video condition. The addition of vestibular information in the wheelchair condition did not improve performance, but the further addition of podokinetic information in the walking condition significantly improved the direction of shortcuts. In contrast, making decisions during exploration did not improve performance in any condition. These results indicate that podokinetic information is the primary component of active survey learning, whereas vestibular information and decision making play little role.

We find that shortcut directions were better than chance in all conditions but were most accurate in the walking condition. Mean absolute angular errors (AEs) were significantly lower in the walking condition than the video condition, whereas the wheelchair and video conditions did not differ. A similar significant pattern was observed for angular constant errors (CEs), with the walking condition being closer to zero than the video or wheelchair conditions in 94% of the trial types. In contrast, there were no main effects of decision making on shortcut performance.

Shortcut distances were longer in the walking condition than in the video condition. This result meant that the walking group undershot far targets less but overshot near targets more and so did not improve performance. The presence of podokinetic information during learning thus had little impact on the accuracy or precision of shortcut length in this medium-scale environment. However, the range of path lengths was compressed in all condi-

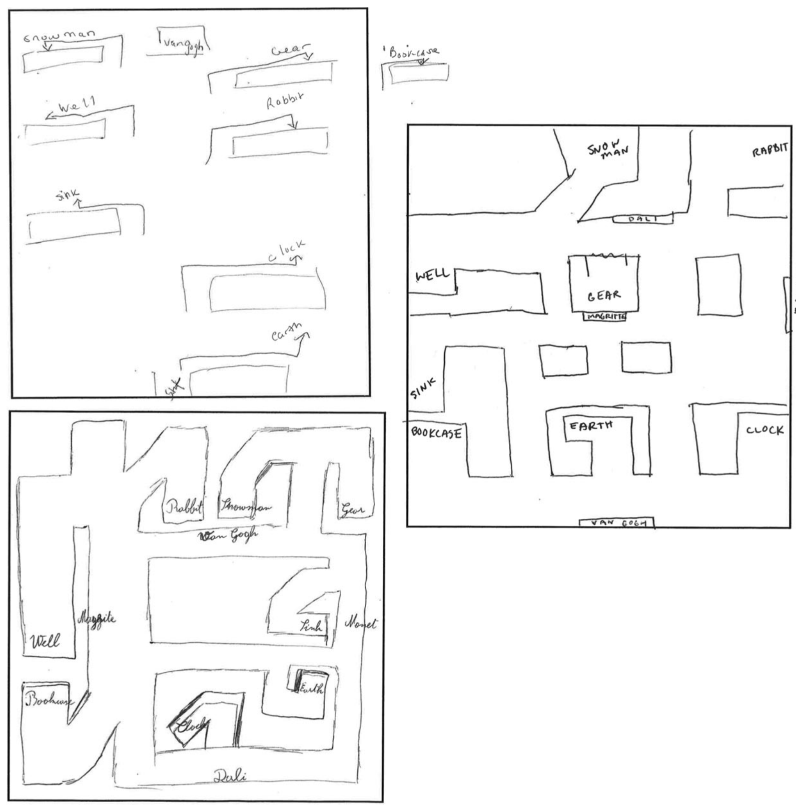

Figure 7. Examples of sketch maps drawn by participants.

tions (see Figure 5), and we suspect that participants were trying to avoid triggering the emergency walls at the boundary of the laboratory, leading them to shorten their response distances.

These results are consistent with the first hypothesis that the active advantage is due to the podokinetic system. Shortcut performance with full information was reliably better than that with vision alone, and in the case of CE better than visual + vestibular information, whereas the latter two conditions did not differ from each other. Together with previous research showing no contribution of vestibular information (Waller & Greenauer, 2007; Waller et al., 2003), the present results support the conclusion that podokinetic information is the primary component of active survey learning.

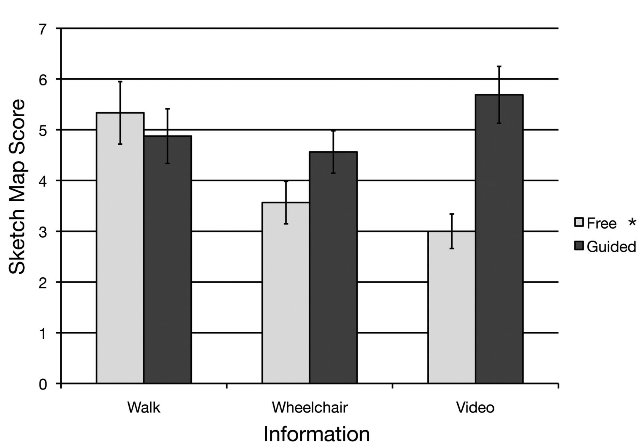

Figure 8. Mean sketch map score for the six experimental conditions. Scores ranged from 1 to 10; error bars indicate between-subject standard error. Significant main effects are indicated by asterisks. * $p < .05$.

There is a caveat, however: It is possible that the influence of vestibular information in our and Waller and Greenauer's (2007) wheelchair condition was weak because it poorly approximated the pattern of stimulation during normal walking. Although the wheelchair was pushed by a walking experimenter at the same mean speed, the vertical component of oscillation was removed and the horizontal linear and angular accelerations were smoothed. Thus, although the data demonstrate a specific role for the podokinetic system in survey learning, it remains possible that a vestibular contribution might also be observed with more natural stimulation.

It is also important to consider the contribution of visual information for self-motion, environmental layout, and location, which included optic flow, binocular disparity, and surface texture. The video conditions were significantly better than chance, indicating that visual information plays a role in survey learning, but its contribution is relatively weak and reduced the mean absolute error by only 8° below the chance level of 90°. It is possible that the restricted field of view in the HMD (63° H × 53° V) reduced the contribution of vision, although that cannot account for the observed differences between conditions. However, Péruch, May, and Wartenberg (1997) found no effect of field of view on visual path integration, suggesting that it may not be a factor in the present experiment. The addition of podokinetic information in the walk conditions served to reduce the mean absolute error 12° further, indicating that it makes a meaningful contribution. Because visual information was available in all conditions we are not in a position to determine the effect of podokinetic information alone, but we can conclude that it is the principle active component of survey learning, over and above passive viewing.

The results are also consistent with the expectation that decision making would not contribute to survey learning. There were no differences in shortcut accuracy between the free and guided groups, indicating that making decisions during the learning phase did not lead to improved survey knowledge. There is thus no evidence that prediction based on a forward model plays a role in survey learning. Otherwise, there was little reason to expect that nominal decision making about which path to follow should facilitate the encoding of metric angles and distances, although this might facilitate the acquisition of route and graph knowledge. There is a small caveat here, however: Although guided participants were led by an experimenter, they were still allowed free head movements, and the travel path of the guided walking group was not completely constrained. Thus, any advantage from an efference copy for preselected movements could have been present in guided as well as free conditions, so it remains possible that unconstrained movements might facilitate survey learning.

A possible concern about the main effect of information is that better performance in the walking condition might be due to encoding specificity. Given that all groups walked during the test phase, the walking group may have benefited simply because walking in a virtual environment at test matched walking in a virtual environment during encoding, whereas the wheelchair and video groups learned the environment in a different context. We have two responses to this concern. First, the visual context actually changed between the learning and test phases for all groups: Learning was performed in the hedge maze, and shortcuts were performed on a textured ground plane. Thus, encoding-specific transfer would have been disrupted in all conditions. Second, the particular actions also changed between learning and test in the walking group, for the paths in the maze during exploration did not match the shortcuts during the test phase. Thus, it is likely that better performance in the walking condition was due to spatial learning based on podokinetic information, rather than encoding-specific transfer.

The present results contradict previous reports that idiothetic information makes no contribution to survey knowledge beyond vision alone (Mellet et al., 2010; Waller & Greenauer, 2007). Such findings are probably attributable to the simple paths used in those experiments, which may be easier to learn visually than more complex paths or environments. In contrast, our results support previous research that found an idiothetic advantage in survey learning on complex paths (Chance et al., 1998; Ruddle et al., 2011; Waller & Greenauer, 2007; Waller et al., 2004). Yet, our results differ somewhat from those of Ruddle et al. (2011). First, whereas they reported an idiothetic advantage for direction judgments in a large-scale but not a small-scale environment, we found such an advantage in a medium-scale environment—probably due to the greater angular complexity of paths in the hedge maze compared to a grid environment. Second, whereas they reported an idiothetic advantage for distance judgments in a small-scale environment, we did not find such an advantage—perhaps because the hedge maze included fewer long straight runs than did the grid environment.

We hasten to point out that the lack of a podokinetic advantage for shortcut distance does not imply that podokinetic information about traversed distance plays no role. Our podokinetic advantage for shortcut direction implies that information about both translation and rotation during walking is combined to learn target directions. The present experiment was not designed to dissociate information for translation and rotation. Previous research (Chance et al., 1998; Ruddle et al., 2011) suggests that idiothetic information for both translation and rotation is important for survey learning in small environments, although visual information about rotation may be sufficient in some circumstances.

We also note that podokinetic information reduced the *SD* of number of visits per object during learning, such that the free walking group explored the environment more evenly than did the free video group. The podokinetic system appears to help participants keep track of the object locations they have previously visited during exploration (see Ruddle & Lessels, 2009), and it presumably contributes to survey learning for the same reason.

Regarding the role of decision making in survey learning, previous research found inconsistent results in desktop VR, based on visual information alone (e.g., Péruch et al., 1995; Wilson et al., 1997). The present experiment was the first controlled study to test decision making in combination with different levels of information. We found no evidence that making decisions about exploration conferred any benefit upon survey learning in any condition. This puts to rest the possibility that the presence of idiothetic information might reveal an effect of decision making, because even with full information there was no difference between free and guided walking. Another implication of this finding is that the strong walking advantage reported by Ruddle et al. (2011) is likely due to podokinetic information, rather than decision making, during exploration. The present result is also consistent with Wan et al.'s (2010) finding that decision making does not contribute to path integration, upon which survey knowledge is presumably based.

The results also offer some insights into the nature of survey knowledge. First, it is striking how poor shortcut performance is, even in the walking condition. Mean absolute angular errors for walking were 62° for men and 79° for women and ranged from 37° for some targets to 101° for others. This finding is consistent with previous experiments, which have reported absolute pointing errors ranging from 20° for some targets (Chance et al., 1998; Waller et al., 2004) to 70° or even 100° for other targets (Chance et al., 1998; Waller & Greenauer, 2007). Our results fall within this range, indicating that the present task is representative of survey learning in other research, despite the complexity of our maze environment. This repeated finding indicates that human survey knowledge for metric locations is very poor.

Examination of individual trial types is particularly informative. Spatial knowledge of some target locations was more accurate than that of others (see Figures 4 and 6). For example, participants learned the direction between some object pairs quite accurately but underestimated the distance (e.g., well to gear); conversely, for other pairs, participants seemed to learn the distance but not the direction (e.g., gear to sink). For certain object pairs, nearly all participants walked in exactly the wrong direction (e.g., snowman to rabbit), suggesting that their knowledge of the target location was consistent but highly incorrect. Taken together, this systematic pattern of different shortcut errors for different targets implies that survey knowledge is a highly distorted version of the environment, even with full information, although it may improve with more exposure (but see Ishikawa & Montello, 2006). One way of visualizing this spatial knowledge is presented in Figure 9, which plots the remembered location of each target object derived from the mean shortcut response of the walking group, assuming an accurate location for the starting object. When one compares this map with the original maze in Figure 1a, it is evident that the degree of not merely metric but also ordinal distortion is rather extreme.

It is interesting to note that the sketch maps exhibited a somewhat different pattern of errors than did the shortcuts. The highest rated sketch maps were drawn by the free walking and guided video groups—the first of which had idiothetic information and made decisions during exploration, and the second of which had neither. Map scores did decline with less idiothetic information in the free condition but not in the guided condition, which produced better sketch maps overall, largely due to the guided video condition. These results are rather surprising, given the latter group's poor performance on the shortcut task. Such discrepant findings suggest that sketch maps may be an inappropriate measure of survey knowledge, despite their frequent use for this purpose. Map drawing is a special skill that involves many cognitive and motor abilities other than spatial knowledge. However, we note that sketch map scores were based on the relative positions of objects and their relationships to hallways, as well as the connections among hallways, and thus may be more indicative of graph knowledge than of survey knowledge.

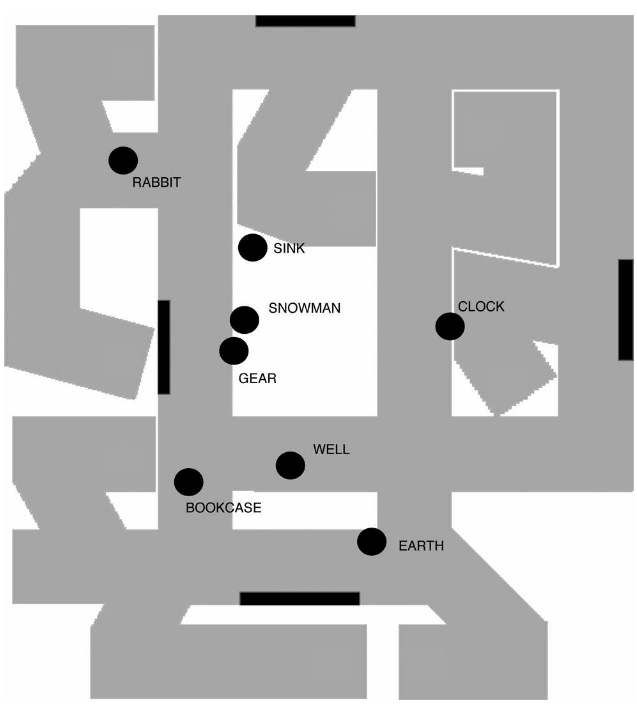

Figure 9. Map of the mean remembered location of each target object for the walking group, based on the mean angular CE and mean path length of shortcuts, on the assumption that the location of the starting object is accurate (compare with Figure 1a). CE = constant error.

The most consistent result of the present study was a large sex difference, with men outperforming women in most aspects of survey learning. Men also had higher scores on all measures of spatial ability and played more video games than did women. It thus seems likely that differences in spatial ability and experience, rather than some aspect of the task, underlie the observed sex difference in the shortcut test. However, the present study was not designed to uncover the source of those differences. Previous research has obtained mixed results regarding sex differences in spatial navigation. Some reports indicate large sex differences (Moffat et al., 1998; Waller, 2000; Wolbers & Hegarty, 2010), whereas others have found little difference or else differences that are narrowly related to specific spatial tasks (Castelli, Corazzini, & Geminiani, 2008; Coluccia & Louse, 2004). Moreover, tests of spatial abilities may be susceptible to stereotype threat (Spencer, Steele, & Quinn, 1999), such that membership in a group that has stereotypically poor skills in one area may adversely affect performance in that area. Women are typically associated with lower spatial skills, and their performance may depend on the level of stereotype threat in a given test of spatial ability (Lawton & Kallai, 2002; Martens, Johns, Greenberg, & Schimel, 2006; McGlone & Aronson, 2006). Our procedure did not take specific steps to alleviate potential stereotype threat, and thus it is possible that this was a factor in the observed sex differences.

Finally, there were also large individual differences in shortcut performance. Even in the free walking group, only about half of the participants had absolute angular errors above chance level (see Figure 3). A third had errors below 60°, and only 15% had errors as low as 20°. The latter value is comparable to the percentage of participants identified by Ishikawa and Montello (2006) as good performers, who acquired accurate survey knowledge of a new environment (AE about 20°) quickly and continued at this level of performance over multiple sessions. Further analysis of individual differences and their relationship to shortcut performance is planned for a future article.

We close by returning to the question with which we began: the potential components of active spatial learning. We conclude, based on the present results and the previous literature, that podokinetic information is the primary component of active learning for survey knowledge. In contrast, vestibular information and cognitive decision making contribute little to active survey learning over and above passive vision alone. We emphasize that these conclusions apply to metric survey knowledge and not necessarily to other forms of spatial knowledge that do not require metric information about the distances and angles traversed. For instance, qualitative route or graph knowledge may play an important role in everyday navigation, and we recently observed a complementary effect of decision making, but not podokinetic information, on graph learning (Chrastil & Warren, 2012b). Further research investigates the role of active attention in the acquisition of both survey and graph knowledge (Chrastil & Warren, 2012c).

In sum, the present experiment demonstrates that, beyond vision alone, podokinetic information is the primary contributor to active learning of metric survey knowledge. In contrast, vestibular information and decision making do not significantly contribute to survey learning.

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Received August 3, 2012
Revision received January 8, 2013
Accepted February 13, 2013 ■