

What Is the Difference between
Active and Passive Spatial Navigation?

By

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Chapter 1

Introduction: Active and Passive Spatial Navigation

It is hard to deny the importance of learning the spatial layout of the environment in our daily lives, as we go to work, do errands, find restaurants, and manage to get back home. In order to navigate successfully, we must acquire some knowledge of the spatial relationships between these locations. Successful navigation might involve scene and place recognition, reliance on salient landmarks, route knowledge, and/or survey knowledge (Wiener, Buchner, & Holscher, 2009). Route knowledge enables one to follow a known path from one location to another, whereas survey knowledge includes some configural information and gives one the ability to take novel shortcuts and detours between locations, traversing paths that have never been taken before. There are thus different types of spatial knowledge that a navigator might acquire during exploration of a new environment, which could depend on the structure of that environment, how it is explored, or the effort devoted to learning it.

Appleyard (1970) was one of the first to note that passengers on a bus seem to acquire only route knowledge of a city, whereas bus drivers have a much greater level of survey knowledge. Taxi drivers may have even greater knowledge than bus drivers, as they navigate novel routes through the city (Maguire, Woollett, & Spiers, 2006). This intuition immediately suggests that the difference between passive exposure and active exploration has important implications for spatial learning. But the anecdote raises more questions than it answers. Is there in fact a systematic difference between active and passive learning? If so, what are the differences in the resulting spatial knowledge? What constitutes “active” exploration specifically – the physical activity of self-motion and its sensory-motor consequences, or the cognitive activity of choosing a route or attending to and encoding particular aspects of the environment?

Chapter 2 of this dissertation will examine previous attempts to answer these questions. Surprisingly, many of these problems remain unsolved. In part, prior research has confused the very notion of active and passive spatial navigation. The various physical and cognitive dimensions of active learning have been confounded in experimental protocols. Many previous experiments have used desktop virtual reality or spatial texts to present the environment, methods that may be insufficient to properly test these questions. Examination of the contribution of information has focused primarily on survey knowledge, and not weaker route or graph knowledge, the knowledge of the connections and adjacencies between locations. Thus, many questions about active and passive spatial learning remain unanswered.

The purpose of this dissertation is to investigate how the mode of exploration in a new environment influences the resulting spatial knowledge. It focuses on the distinction between active and passive spatial learning, and asks how they contribute to graph and survey knowledge. Several different components of active learning were independently manipulated to determine their relative contributions. The results suggest idiothetic information from self-motion makes a significant contribution to survey knowledge. Cognitive decision-making makes a significant contribution to graph knowledge, while also interacting with idiothetic information in its contribution to graph knowledge. Finally, additional tasks to orient attention to different aspects of the environment do not appear to contribute significantly to graph knowledge.

This dissertation is organized as follows. Chapter 2 reviews the existing empirical literature on active and passive spatial navigation and lays out what questions have been resolved and what gaps remain. Chapter 3 experimentally tests the

contributions of proprioception/motor efference, vestibular input, and cognitive decisions to survey knowledge. Chapter 4 experimentally tests the impact of these same factors on graph knowledge, an intermediate level between route and survey knowledge. Chapter 5 experimentally tests the contribution of attention to graph and survey knowledge. Finally, Chapter 6 discusses how these results relate to each other and to the broader question of active and passive spatial learning.

Chapter 2

Background Literature

The questions raised in the Introduction provide a convenient starting location to begin the literature review. What are the systematic differences in spatial knowledge between active and passive navigation? How are survey and route knowledge affected by active navigation? Are there differences between the physical and cognitive components of active navigation? What does “active” even mean?

This literature review begins by arguing that the active/passive dichotomy is too coarse a distinction, for “active” learning encompasses a number of potential components. The goal is to tease out the active and passive contributions to these types of spatial knowledge, and identify gaps in the existing literature. The review starts with the sensory-motor components of physically walking through an environment, and then pursues cognitive mechanisms that may play a role in active learning. Next, there is a discussion about how literature on spatial updating contributes to larger issues of spatial navigation. The review then turns to attention and working memory, which operate in tandem to selectively encode different aspects of the environment, and active manipulation of spatial information in working memory can yield greater learning. Research on these topics has been hampered by inconsistent methods, making both qualitative and quantitative comparisons difficult. Throughout the review, these inconsistencies will be highlighted, while firm conclusions will be drawn wherever possible. While there are a number of interesting neural correlates related to landmark, route, and survey learning, it has been difficult to assess active and passive contributions to spatial learning through neuroimaging methods, since these have by necessity little idiothetic information. Thus, the neural correlates of active and passive spatial learning will not be discussed here.

The results of the empirical literature suggest that there is a relation between active exploration and the acquisition of spatial knowledge. Specifically, examination of the literature suggests that the idiothetic information available during walking contributes to metric survey knowledge, and appears to interact with attention. Some aspects of places and landmarks can be learned without much effort, but full route and survey knowledge require the allocation of attention and encoding in working memory. Different components of working memory may be responsible for encoding certain aspects of the environment, while mental manipulation of spatial information may also play a role in learning.

Active and Passive Spatial Learning

Despite Appleyard's (1970) observation, studies comparing active and passive spatial learning have yielded surprisingly mixed results. One reason for the heterogeneous findings is that active exploration actually involves several complex activities that are often confounded in experimental designs.

Components of Active Learning

To test passive learning, experimenters typically present visual information about the path of self-motion through the environment – such as the sequence of views seen by an explorer – to a stationary observer in the form of a video or series of slides. Active learning, however, may not be limited to physical movement alone. In addition to the motor control of action, active learning could include the resulting sensory information about self-motion and several cognitive processes (Gaunet, Vidal, Kemeny, & Berthoz, 2001). Specifically, we can identify five distinct components of active exploration that

potentially contribute to spatial knowledge: (a) efferent motor commands that determine the path of locomotion, (b) reafferent proprioceptive and vestibular information for self-motion (a and b are collectively referred to as *idiothetic information*, Mittelstaedt & Mittelstaedt, 2001), (c) allocation of attention to navigation-related features of the environment, (d) cognitive decisions about the direction of travel or the route, and (e) mental manipulation of spatial information. These components may be grouped into those that involve physical activity—motor control and reafferent information—and those that involve cognitive activity—attention, decision-making, and mental manipulation (Wilson, Foreman, Gillett, & Stanton, 1997). For present purposes, navigation that involves any or all of these five components will be referred to as “active”. But the aim is to refine the concept by identifying which of these components actually play a role in spatial learning. Thus, this review will elucidate their relative contributions to particular forms of spatial knowledge and whether they act independently or interact in some way.

On the basis of theoretical considerations, one would expect these components of active learning to differentially affect what the explorer learns about specific aspects of spatial structure. The first hypothesis is that idiothetic information plays an essential role in the acquisition of survey knowledge. Survey or “map” knowledge is believed to depend upon information about the metric distances and directions between locations, such as that provided by the motor, proprioceptive, and/or vestibular systems, together with a process of path integration. Although passive vision also provides information about the depth and visual direction of objects, spatial perception is subject to large affine distortions (Koenderink, van Doorn, & Lappin, 2000; Loomis, Da Silva, Fujita, &

Fukushima, 1992; Norman, Crabtree, Clayton, & Norman, 2005). The idiothetic systems specifically register distance and turn information along a traversed path, providing a basis for path integration, and thus might be expected to improve the accuracy of survey knowledge.

The second hypothesis is that active decision-making about the path of travel is sufficient for the acquisition of route knowledge, in the absence of idiothetic information. Given that route knowledge is believed to consist of a sequence of turns at recognized locations (place-action associations) along a learned route (Siegel & White, 1975), making decisions about turns on one's path should be sufficient to acquire useful route knowledge, without metric information.

The third hypothesis is that the acquisition of route and survey knowledge depends on the allocation of attention to corresponding environmental properties. For example, assuming that place-action associations depend on reinforcement learning mechanisms, explicitly attending to conjunctions of landmarks and turns should facilitate route learning (Chun & Turk-Browne, 2007; Sutton & Barto, 1998). Similarly, attending to information about the relative spatial locations of places should enhance survey learning. On the other hand, to the extent that object encoding and recognition are automatic processes (Duncan, 1984; O'Craven, Downing, & Kanwisher, 1999), landmark learning should not require the allocation of attention. Finally, these components may interact. For instance, actively making decisions about one's route may lead the observer to attend to different features of the environment than when following a prescribed route.

Note that many experiments make use of desktop virtual reality setups (desktop VR), in which participants use a joystick to steer around a virtual environment presented

on a monitor. This process is quite different from walking around an environment: although desktop VR does involve some physical hand movements, actual walking provides qualitatively different motor, proprioceptive, and vestibular information.

Navigation vs. Spatial Updating

The issue of active and passive learning has also come up in recent research on the topic of spatial updating. Spatial updating occurs when an observer maintains information about the spatial relations among objects as he or she moves around in the environment. Spatial updating is thus closely related to path integration and probably shares many of the same mechanisms, including reliance on visual and idiothetic information. However, there are important methodological differences between spatial updating and navigation paradigms that make it difficult to compare the findings. Experiments on spatial updating typically present a small set of objects in a central location that are all viewed simultaneously, so the participant can perceive the spatial relationships between the objects. In navigation experiments, by contrast, the observer is typically embedded in a larger environmental layout and views objects sequentially, so he or she must path integrate between them to derive their spatial relationships. Despite these differences, some researchers have used results from spatial updating to support claims concerning navigation. Active and passive spatial updating should not be confused with active and passive navigation. An attempt will be made at clarifying this rather unwieldy body of literature.

Limitations of the Literature

To illustrate some of the challenges in conducting research on active and passive learning, we begin with a few introductory examples. Gaunet, Vidal, Kemeny, and

Berthoz (2001) attempted to isolate the motor/proprioceptive component of active learning using desktop VR. They asked three groups to follow routes in novel environments: active, passive, and snapshot. The active group physically handled a joystick to steer but did not make decisions about the travel path; the experimenters verbally instructed participants to “go straight” or “turn left.” The passive group simply watched a video of the same route through the environment, while the snapshot group saw sample views taken from the video instead of continuous motion. The authors failed to find an active/passive effect: there were no group differences in pointing back to the start location from the end of the path, or in a scene recognition task. The only difference occurred in route drawing, and even then there was no difference between the active and passive groups; rather, the snapshot group had larger distance and angle errors. The implication of these results is that some spatial knowledge can be obtained from all three modes of exploration. However, the absence of an active advantage might be due to the reduced motor and proprioceptive information when using a joystick, or the lack of decision-making during exploration.

Other evidence points to an active/passive effect. Carassa, Geminiani, Morganti, and Varotto (2002) reported that self-controlled exploration with a joystick in desktop VR led to greater wayfinding abilities than passively following an avatar through the environment. However, this result is confounded by the fact that the active group was instructed to use the most efficient exploration procedures, which could have promoted different spatial processing; in addition, the visual input was not equated for the two groups. Some research suggests that it may be the motor component that yields an active advantage. Farrell, Arnold, Pettifer, Adams, Graham, and MacManamon (2003) found

that using a keyboard both to actively explore and to follow a prescribed route in desktop VR led to fewer errors when tested in a real environment, as compared to participants without prior experience in the environment; in contrast, passively watching a video of the route did not yield such an improvement. However, visual input was not equated in the active exploration and route-following conditions, and it is not clear whether the difference between route-following and passive viewing conditions is due to motor control of the keyboard or to a difference in attentional deployment.

These studies highlight some key challenges facing research on active and passive navigation. First, the use of desktop VR fails to provide appropriate idiothetic information about self-motion. Motor control of a joystick or keyboard is qualitatively different from that of legged locomotion, and the resulting proprioception specifies the joystick deflection or the number of key presses rather than properties of the step cycle, while vestibular information specifies that the observer is stationary. These sources of information could be vital to keep track of the distance traveled and the magnitude of body rotations. The size of the display may also affect performance on spatial tasks (Tan, Gergle, Scupelli, & Pausch, 2006). In addition, the relation between motor efference and visual reafference in desktop VR is different from that in walking, and thus may affect visual path integration.

Second, it is difficult to isolate and test the active and passive components. The difference between the active and passive groups in Gaunet et al. (2001), for example, consisted of only the motor and proprioceptive information arising from use of a joystick. The null result in this study thus may not be surprising. To adequately test the contribution of physical activity, an ideal experiment would compare one group that

walked around in the environment with full locomotor control and information about self-motion, guided by an experimenter (to prevent decision-making), with a group that watched a matched video of that exploration.

Third, it is important to equate the size and visibility of the environments. Being able to see the entire layout at once may yield different effects than being immersed in the environment and moving around to view the layout. In the former case the spatial relations among objects are immediately visible, whereas in the latter case they must be determined via path integration.

Finally, it is important to match the views seen by participants to the extent possible, including the visual angle of the display. Often, researchers allow active participants to freely explore the environment, but guide passive participants through a standard pre-planned route. The active groups may thus have exposure to the environment that the passive groups do not, making comparisons uncontrolled. Both Carassa et al. (2002) and Farrell et al. (2003) failed to match the route of exploration of the passive groups with those of the active groups.

If this review of active and passive learning were limited to studies using real-world or ambulatory virtual environments with walking observers, matched views, and appropriate idiothetic information, then the discussion would be very short. Even the most complete studies tend to have one or more of these limitations. Thus, this review will draw some preliminary conclusions about active and passive spatial learning from the available literature, bearing in mind that they must be clarified by further research.

Idiothetic Information, Decision-making, and Attention in Spatial Learning

This section addresses the contributions of idiothetic information and decision-making during exploration to landmark, route, and survey learning; it also discusses attention as it relates to these factors. This section begins by exploring attempts to cross aspects of physical movement with the ability to make decisions about exploration.

An illustrative example comes from the developmental literature. When young children actively explore a playhouse, they are better at finding novel shortcuts and reversing routes than children who are led around or carried around by their parents (Hazen, 1982). Thus, making route decisions appears to improve children's spatial learning over being led on a route; such decision-making may also drive attentional allocation. On the other hand, in this instance idiothetic information did not appear to contribute to spatial learning in children, for there was no advantage to being led over being carried. When navigators can make their own decisions about the direction of travel, they may then test predictions about how their own actions affect their subsequent views of the environment (Gibson, 1962; James, Humphrey, & Goodale, 2001) or the change in direction and magnitude of their own movements (Larish & Andersen, 1995).

Most research that focuses on decision-making tends to use desktop VR, making it difficult to assess the role of idiothetic information. Conversely, research on idiothetic information tends to ignore the role of decision-making and attention. This section also examines the relation between research on spatial updating and the question of active and passive spatial learning. The scale and visibility of the environment are important factors when interpreting these two literatures.

Motor Control and Decision-Making in Desktop VR

A comprehensive examination of the active and passive distinction was carried out in a series of experiments by Patrick Péruch, Paul Wilson, and their colleagues using desktop VR. Péruch, Vercher, & Gauthier (1995) first examined differences between active and passive learning in a semi-open environment, using a within-subject design. In the active condition, participants were able to explore freely using a joystick, giving them both motor and cognitive control. In the passive-dynamic condition, they watched a video of exploration, while in the passive-snapshot condition they viewed slides of exploration. During the test phase, they were asked to navigate through the environment to each of four landmarks, taking the shortest route possible. The active condition led to significantly higher performance on this task than the passive-dynamic condition, which in turn was significantly better than the passive-snapshot condition. There were also individual differences, such that some people tended to perform well in all conditions while others fared poorly throughout.

This finding stands in contrast to that of Gaunet, et al. (2001), who reported no difference between the active and the passive-dynamic conditions; hence, the effect might be attributable to decision-making during exploration in the present experiment compared to a prescribed route in Gaunet, et al. (2001). However, Péruch, et al. (1995) also provided more exposure to the environment: whereas participants in Gaunet et al. (2001) saw a given section of a route only once, the present participants learned a relatively small semi-open environment and typically traveled through a given section two to three times, which could have promoted active learning. In addition, Péruch, et al. (1995) used different environmental layouts in each condition, and the passive video was not matched to the active condition, so the effect could be due to variations between conditions. Thus,

it is unclear whether it is active motor control, active decision-making, the exposure to the environment, or the differences in layout that accounts for the active advantage.

To address some of these problems, Wilson, Foreman, Gillett, & Stanton (1997) conducted an experiment with five groups in a yoked design, using desktop VR with a keyboard (where “active” denoted decision-making). The active-with-movement group both made decisions about their path and controlled the movement by pressing the keyboard, whereas the passive-without-movement group simply viewed the corresponding display. The active-without-movement group decided where to go, but communicated the decision to yoked passive-with-movement participants, who carried out the action with the keyboard. The control group simply performed the test trials without previous exposure to the environment, and should thus perform at chance. In the test phase, participants were virtually dropped at one of three landmarks and asked to point to the other two landmarks; they also drew a map of the environment. All experimental groups had significantly smaller pointing errors than the control group, indicating that some survey learning had taken place. However, there were no differences between any of the experimental groups, such that neither motor nor cognitive activity proved to have an effect. In a second experiment, the authors used a simpler environment and test tasks similar to those of Péruch et al. (1995). Even so, they found no differences between the experimental groups, and only one significant difference between the control group and the passive group.

To reconcile their opposing findings, Wilson and Péruch (2002) joined forces to examine the issue of motor and cognitive control, again using desktop VR. They designed a yoked setup in which active participants explored the environment while

passive viewers either sat next to them and watched their movements together with the display, or only viewed a video of the display. The results in this case show that passive participants were more accurate at pointing to the targets when sitting next to the active participants than when watching the video; they were also more accurate than active participants in wayfinding. These results contradict both the previous findings of either no difference (Wilson et al., 1997; Wilson, 1999) or better performance by active observers (Péruch et al., 1995; Tan et al., 2006). To resolve these inconsistent findings, the authors tested both the active and passive conditions in a within-group design, with all yoked pairs sitting side-by-side during exploration. In this case, they found no differences between conditions for any of the dependent measures.

A related experiment investigated the contribution of active and passive exploration to scene recognition in desktop VR. Christou & Bühlhoff (1999) paired active explorers who used a track ball to explore a virtual house with passive observers who watched a video of the display. They found that participants were best at recognizing scenes of the environment based on views they had previously observed, and were also better at recognizing scenes from novel views than from mirror-reversed familiar views. However, there was no difference between the active and passive groups: both showed higher accuracy and faster reaction times for familiar views than for novel views of the same environment. The results are consistent with the acquisition of view-based scene representations, but show that active learning is no better than passive learning, even for recognizing scenes from novel viewpoints. When passive observers only viewed snapshots of the display, performance on novel views dropped dramatically,

to the level of mirror-reversed views. This result confirms an advantage of continuous visual motion during exploration of the environment.

Taken together, these results offer little support for a role of decision-making in spatial learning. Any effects of active vs. passive exploration in desktop VR are small and unreliable, and may be susceptible to minor procedural differences. In addition, the reduced motor and proprioceptive information from small movements of a joystick or keyboard does not adequately test the idiothetic contribution. We thus take a more detailed look at the role of idiothetic information in studies of active walking.

Idiothetic Information During Walking

Much of the research on idiothetic information during locomotion goes beyond desktop VR by using ambulatory VR – environments that are presented in a head-mounted display with a head-tracking system, so the participant can walk through the virtual environment. In an early study, Grant & Magee (1998) reported results consistent with an idiothetic contribution. Participants were guided on a prescribed route in a large-scale real environment and a matched virtual environment with an interface that allowed them to walk in place, so decision-making and the visual sequence were controlled; they were subsequently tested on finding locations in the real environment. Participants who walked in the real environment were faster to find locations in the test than those who walked in place (reducing idiothetic information) or used a joystick in the virtual environment. The walk-in-place group also showed some advantages over the joystick group, such as taking shorter paths in the test. These results suggest a role for idiothetic information, however, the real-environment group also had a larger field of view and free head movements compared to the VR groups.

Additional studies have also examined the contributions of idiothetic information on wayfinding or route knowledge. Ruddle & Lessels (2009) had participants search for hidden objects in a room-sized virtual environment. They found better performance for those who walked compared with those that physically rotated but translated with a joystick and those that used a joystick for both rotation and translation. In contrast, Riecke et al., (2010) reported an advantage only for physical turns over joystick alone. They found that the addition of physical translation only aided learning by leading to less total distance traveled during search.

Ruddle, Volkova, Mohler, & Bühlhoff (2011) examined body-based contributions to route knowledge. They had some participants walk in a virtual environment to follow a specified route, and then asked them to retrace the route and repeat the out-and-back route several times. Other participants made physical rotations, but used a joystick for the translation component. Overall, the walking group had fewer errors, primarily when traveling the reverse direction on the route. Ruddle, Volkova, & Bühlhoff (in press) similarly found an advantage for walking over physical rotations and purely visual exploration of a virtual marketplace. In this experiment, participants searched for four target objects, and then after returning to the start location they had to find the objects again and estimate distances and directions to the other objects. In a small-extent environment, the walking group traveled less to find the target objects and had more accurate estimates of the distance between targets. In a large-extent environment, participants either walked using an omni-directional treadmill, walked with a linear treadmill but used a joystick for rotations, physically rotated but used a joystick for translations, or used a joystick for both rotations and translations. In the larger

environment, those participants who walked using a treadmill (either omni-directional or linear) had more accurate estimates of distance and direction between targets. Together, these two studies indicate that motor and proprioceptive information are vital to learning routes, as well as to some survey knowledge, while rotational information contributes minimally to wayfinding.

Most other examinations of idiothetic contributions to spatial learning focus primarily on survey knowledge. Chance, Gaunet, Beall, & Loomis (1998) examined spatial learning from path integration in fairly simple virtual mazes, which contained 1 to 3 target objects separated by barriers. The experimenters varied the availability of idiothetic information by having participants walk or steer with a joystick on a prescribed path through the environment, thus eliminating decision-making. Participants were instructed to keep track of the object locations along the path; at the end of the path, they reported the location of each object by referring to the hands of a clock to indicate their estimate (Experiment 1) or turning to face the object's location (Experiment 2), without feedback. Participants who physically walked had lower absolute pointing errors than those who used a joystick to traverse the path, but only after considerable exposure to the testing procedures and environments (on the third trial in each maze, Experiment 1), or with a path that had no decision points, possibly allowing for more attention to the location of the objects (Experiment 2). However, participants who used a joystick to traverse linear segments but physically turned in place to change direction were in between, and not significantly different from either group. These findings indicate that idiothetic information about translation and rotation during locomotion (and possibly

each separately) is important to keep track of one's position and acquire spatial relations in the environment.

Waller and Greenauer (2007) conducted a similar experiment in which participants traveled a prescribed path through a series of hallways with several noted locations. The Walk group had visual and idiothetic information, the Wheeled group had only visual and vestibular information, and the Still group viewed videos of the display. Participants were asked to point and estimate distances between all possible pairs of locations. In contrast to Chance et al. (1998), there were no overall differences in pointing errors between conditions, but there was a significant advantage for the Walk group when the pairs of locations were linked by a large number of turns. Mellet, Laou, Petit, Zago, Mazoyer, and Tzourio-Mazoyer (2010) likewise found no differences in relative distance judgments when comparing those who learned object locations by walking in a simple real hallway and those who learned by using a joystick in VR. Taken together, these ambulatory studies suggest a contribution of motor and proprioceptive information (although perhaps not vestibular information) to spatial learning, but only on sufficiently complex paths and after repeated exposure to the environment.

The environments used in these last several studies were fairly simple, with few, if any, path intersections or choice points. They were also fairly small, the size of a room or a building, although objects were not simultaneously visible. It is possible that idiothetic information is more useful for spatial updating in a small-scale environment than for learning survey knowledge in a large-scale space. Longer paths may lead to increasing drift in path integration, particularly vestibular information, eventually rendering it unreliable for estimating distance and direction (see Collett, Collett,

Chameron, & Wehner, 2003; Etienne, Maurer, Boulens, Levy, & Rowe, 2004; Etienne, Maurer, & Séguinot, 1996; Müller & Wehner, 2010 for the drift and resetting of path integration in animals). To test this hypothesis, Waller, Loomis, & Steck (2003) varied the magnitude and fidelity of vestibular information that participants had access to while exploring a large real-world environment. Some participants were driven in a car on a route through the environment while receiving full visual and vestibular information. Others rode in the car while viewing a video in an HMD that matched the vestibular input, but with a reduced field of view. A third group viewed the same video while the car traveled on a different route, such that visual and vestibular information were incongruent. A final group watched the video while sitting still, receiving no vestibular input. Participants were asked to estimate distances and directions between all 20 possible pairs of locations on the route. Those who had full visual and vestibular information were more accurate than any of the other three groups, which did not differ from each other. These results suggest that vestibular input only contributes to survey knowledge of a large environment when it is paired with a large field of view. The differences between the full information and congruent groups might be due to the field of view, but could also be attributed to active head turns, or visual fidelity in the full information condition.

An additional limitation of this experiment is the absence of proprioceptive information. To remedy this, Waller, Loomis, & Haun (2004) presented both proprioceptive and vestibular information during exploration. Participants traveled a prescribed route either by walking in a virtual environment while wearing an HMD, viewing a matched video in the HMD while sitting, or watching a matched video in the

HMD that was smoothed to minimize head jitter and rotation. They kept track of five locations along the route, and at the end gave pointing estimates between all possible pairs. Participants who walked through the environment were more accurate than those who watched either of the videos, indicating that idiothetic information contributes to survey knowledge of the environment. It remains to be determined whether this effect is due to the motor and proprioceptive information, the vestibular information, or their combination.

Another line of evidence stems from research on alignment effects in spatial cognition. Early work had found that participants are more accurate in making spatial judgments when they are aligned with the initial learning orientation (e.g. to a map), than when facing the opposite direction (Evans & Pezdek, 1980; Presson & Hazelrigg, 1984; Richardson, Montello, & Hegarty, 1999; Thorndyke & Hayes-Roth, 1982). Such alignment effects imply that the learned spatial representation is orientation-specific. However, recent evidence suggests that even a small amount of motor and proprioceptive information can reduce alignment effects (Richardson et al., 1999; Rossano, West, Robertson, Wayne, & Chase, 1999; Sun, Chan, & Campos, 2004). Sun, Chan, and Campos (2004) found that participants who walked on a prescribed route through a real building during exploration had lower overall pointing errors to landmarks than those who rode a stationary bike on the same route through a virtual building, presented in an HMD. However, they reported no alignment effects in either group. Alignment effects even disappeared when exploration was controlled with a mouse, despite reduced motor and proprioceptive information. Passively watching a video of the corresponding display, however, resulted in the same kinds of alignment errors observed in map

learning. These results indicate that very little motor efferent and proprioceptive information, without vestibular information, may be sufficient to yield orientation-free spatial knowledge. The absence of alignment effects should be noted with caution, as it does not necessarily correlate with superior spatial knowledge. Rather, their absence indicates that spatial knowledge is not view-dependent, although this conclusion seems at odds with the results of Christou and Bühlhoff (1999) for scene recognition. Better spatial knowledge is acquired when actively walking, but this could be due to a larger field of view in the real environment.

In sum, the evidence offers qualified support for an idiothetic contribution to spatial learning. The addition of motor, proprioceptive, and possibly vestibular information due to walking during exploration appears to improve performance on survey tasks such as pointing, over and above passive vision alone (Chance et al., 1998; Waller et al., 2004). Similar results are also seen in route learning and wayfinding tasks (Riecke et al., 2010; Ruddle et al., 2011, in press). This pattern seems to hold especially with complex paths or repeated exposure to the same environment (Chance et al., 1998; Waller & Greenauer, 2007), suggesting that passive vision may be sufficient for simple environments (Mellet, et al., 2010) and that idiothetic learning may build up over time. Other positive results could be attributable to a larger field of view or free head movements in the walking condition (Grant & Magee, 1998; Sun et al., 2004; Waller, et al., 2003). Thus, the general pattern of results is consistent with a role for idiothetic information in active spatial learning, although the relative contributions of locomotor efference, proprioception, and vestibular information remain to be determined.

However, these studies did not attempt to control for the allocation of attention during exploration, which may also be an important contributor to active learning. It is possible that attention is allocated to different aspects of the environment in active and passive experimental conditions. For example, active exploration requires greater interaction with the environment, which may lead participants to attend more to the spatial layout (Wilson & Péruch, 2002). Thus, we turn to possible effects of attention during exploration.

Attention to Spatial and Nonspatial Properties

Wilson, et al. (1997; Wilson, 1999) speculated that the null results in their desktop VR experiments might be explained by similar patterns of attention in both active and passive conditions. They had instructed all participants in both conditions to pay attention to the spatial layout. Thus, they hypothesized that when passive observers attend to spatial properties, they perform as well as active explorers.

Conversely, other results suggest that active/passive differences appear when attention is directed to nonspatial aspects of the environment. Attree, et al. (1996; Brooks, et al., 1999) instructed participants to attend to objects while taking a route through a desktop virtual environment, specifically to “study the objects...and try to find an umbrella which may or may not be there.” Active participants explored the environment using a joystick, and performed better on subsequent recall tests of spatial layout than passive participants who viewed a corresponding display. On the other hand, passive participants were only marginally better than active participants on object memory. These results suggest that when passive observers attend to spatial properties they learn the layout as well as active observers, but when they attend to objects their

layout learning suffers. In contrast, active explorers may attend to the spatial layout in order to successfully navigate through the environment even when instructed to attend to objects, so they acquire better spatial knowledge than passive observers in that condition.

However, Wilson (1999) found no active advantage for spatial learning when attention was directed to objects. Wilson & Péruch (2002) pursued this issue further by instructing half of their yoked active/passive participants to attend to the spatial layout, and the other half to attend to the objects in the environment. The object attention group recognized more objects than the spatial attention group, and passive participants in the spatial group recalled fewer objects than the three other groups. However, spatial tests of pointing and judging distance revealed no differences between any of the groups. The only effect on spatial learning was that the spatial attention group was better at drawing a map than the object attention group; consistent with the authors' original hypothesis, active participants were only marginally better than passive participants. These results cloud the picture further, leading Wilson & Péruch (2002) to conclude that findings of attentional influence on spatial learning are unreliable.

Taken together, there is no consistent evidence that directing attention to spatial layout or objects influences spatial learning, although it does appear to affect object learning. Part of the inconsistency may be due to the use of different measures of spatial knowledge: tests of layout recall seemed to show an attentional effect (Attree, et al., 1996; Brooks, et al., 1999), whereas standard tests of survey knowledge such as pointing and distance estimates did not (Wilson, 1999; Wilson & Péruch, 2002). However, this failure to find an effect of attention on survey tasks in desktop VR is not particularly surprising. The acquisition of survey knowledge depends on metric information during

learning, and the evidence just reviewed indicates that it is provided by idiothetic information during walking. Desktop VR is thus an inherently inadequate paradigm in which to test the role of attention, and we return to the question in the section on Attention and Incidental Spatial Learning.

It remains possible that active exploration may provide an advantage because the greater interaction with the environment leads participants to attend to spatial layout, but as yet there is little support for this hypothesis. Thus, the active advantage during walking discussed in the previous section (Idiothetic Information During Walking) appears to be attributable to idiothetic information, rather than to increased spatial attention in the active condition.

Idiothetic Information in Spatial Updating

The active/passive distinction has also become important in the recent literature on spatial updating. For present purposes, we will consider spatial updating to be the problem of keeping track of the spatial relations between the observer and a small array of objects as one moves around the environment. Spatial updating is closely related to the problem of path integration, but the experimental paradigms have important differences. In most spatial updating tasks the environment usually consists of a small array of objects that can be viewed all at once, and the task emphasizes maintaining the spatial relations among objects as one's viewpoint changes. In contrast, in path integration tasks the observer is typically embedded in a larger layout of objects that cannot be viewed simultaneously, and the task emphasizes keeping track of one's position and orientation within that environment; this is typically assessed by judgments of the location of the observer's starting point. Both spatial updating and path integration

require measuring the distances traveled and angles turned by the observer, and probably share common mechanisms of integrating information about self-motion. However, the tasks are sufficiently different that it is not clear whether experimental results transfer from one paradigm to the other. Thus, the main findings from the spatial updating literature will be summarized here (see Chrastil & Warren, in press, for more detailed analysis).

It is important to point out a key difference between the spatial learning and spatial updating literatures. Whereas the active/passive question in spatial learning applies to movement *during* exploration and learning, in spatial updating it typically applies to movement *after* an object array has already been learned. There is no evidence that active movement while examining a small array of objects aids spatial learning (provided that there is sufficient static information to specify the 3D configuration). Participants allowed to freely walk around while learning a spatial array were no more accurate at later spatial judgments than those who viewed the display from a single monocular viewpoint (Arthur, Hancock, & Chrysler, 1997), and free movement during learning does not preclude alignment effects (Valiquette, McNamara, & Smith, 2003). Thus, active/passive spatial updating is chiefly concerned with whether a known set of object relations is updated during locomotion. Given that spatial learning of a layout of objects presumably depends on keeping track of their positions as one moves about, evidence from spatial updating and path integration may have implications for spatial learning. In addition, some wayfinding tasks may appear on the surface to require path integration. However, one cannot assume that all wayfinding requires accurate survey knowledge derived from path integration or spatial updating. Alternative navigation

strategies based on sequences of views, route knowledge, or the ordinal relationships among objects may be sufficient for many wayfinding tasks.

The results from the spatial updating literature suggest that spatial updating during movement is a fairly automatic process (Farrell & Robertson, 1998; Rieser, Guth, and Hill, 1986; Rieser, 1989), while imagining or ignoring movement appears to be an effortful process (Farrell & Thomson, 1998). These results indicate that idiothetic information and the corresponding visual imagery cannot be easily decoupled, possibly due to the long-lasting and functionally useful calibration between visual and idiothetic information for self-motion (Rieser, 1989).

The evidence suggests that spatial updating is automatic with physical movement, but it is unclear exactly which components of idiothetic information are vital to this process, or whether visual information is also sufficient. Féry, Magnac, and Israël (2004) found that vestibular information is not sufficient, but rather some measure of control over when the rotations start and stop using motor or proprioceptive information is important. In contrast, Wraga, Creem-Regehr, & Proffitt (2004) found that motor efference added little to spatial updating beyond the contributions of vestibular input; however, they did find that the combination of vestibular and proprioceptive information lead to superior performance over visual motion alone. While vestibular and proprioceptive information provide an advantage over visual information alone, there is some evidence that the latter might be sufficient for spatial updating, but possibly only in environments that had previously been learned by walking (Riecke, Cunningham, & Bühlhoff, 2007).

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, Klatzky, Golledge, Cicinelli, Pellegrino & Fry, 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 and Haun, 2004; Kearns, 2003; Klatzky, Loomis, Beall, Chance, and Golledge, 1998; Tcheang, Bühlhoff, & Burgess, 2011).

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; Shelton & McNamara, 2001; Tarr, 1995). 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 views. Spatial updating could mitigate the limitations of viewer-centered 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). Examinations into this question revealed that vestibular information appears to be sufficient for spatial updating, whereas neither motor/proprioceptive information nor the cognitive control and information about the magnitude of the change in viewpoint are essential (Simons & Wang, 1998; Wang & Simons, 1999; Waller, Montello, Richardson, and Hegarty, 2002). However, there have also been a few reports limiting the scope of these effects (Motes, Finlay, & Kozhevnikov, 2006; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Teramoto & Riecke, 2010).

On balance, the literature is generally consistent with the occurrence of spatial updating during active movement. Thanks to an established calibration between idiothetic and visual information for self-motion, active movement produces coordinated updating of viewer-centered object locations and visual imagery, and tends to reduce view-dependent alignment effects. A couple of dissenting reports suggest that spatial updating may be compromised by larger rotations or more difficult recognition tasks. Active updating is clearly based on idiothetic information, although there are conflicting results about whether vestibular information is sufficient or if motor and proprioceptive information are necessary. There are some suggestions that visual information for place recognition or self-motion may be sufficient for spatial updating under certain conditions.

Conclusions: Idiothetic Information, Decision-Making, and Attention

This section has examined the contributions of idiothetic information, decision-making and attention to spatial learning, primarily using VR techniques. The pattern of evidence reviewed so far indicates that idiothetic information during walking plays an important role in active navigation, a pattern that is generally consistent across the spatial learning, path integration, and spatial updating literatures, with some exceptions. In principle, idiothetic information could help an explorer keep track of their position and orientation and relate the spatial locations of objects as they walk around the environment. In contrast, there is little evidence that making decisions about one's path or attending to the spatial layout (as opposed to isolated objects) during exploration makes a contribution to spatial learning. However, these conclusions must be regarded as preliminary because the available evidence is limited and inconsistent.

One important limitation is that studies of decision-making and spatial attention discussed so far have been done in desktop VR, which has failed to yield reliable evidence of any active advantage in spatial learning, whereas most studies of idiothetic information have been done using prescribed routes in ambulatory VR. An exception is a recent study by Wan, Wang, and Crowell (2010), who found no evidence that path choice improved path integration in the presence of full idiothetic information. However, the authors did not examine its influence on the resulting spatial knowledge. Thus, there is no research investigating the contribution of these three components to spatial learning in the same experimental paradigm, especially regarding route knowledge. As a consequence, possible additive effects or interactions between them remain unexamined. Further studies in ambulatory environments are needed to investigate whether decision-making and spatial attention contribute to spatial learning when normal idiothetic information is also available.

Second, the spatial learning literature has focused primarily on metric survey knowledge, as opposed to weaker route, ordinal, or topological knowledge. In most cases, the research involves survey tasks such as standing (or imagining standing) at one location and pointing to other locations, or making distance judgments between locations. These tasks probe metric knowledge of the environment, which appears to depend on the metric information provided by the idiothetic systems. This test of metric knowledge might explain the dependence of an active advantage on idiothetic information. Only a few studies have tested other tasks that could be based on weaker spatial knowledge (e.g. Grant & Magee, 1998; Hazen 1982; Péruch et al, 1995; Ruddle et al., 2011; Wilson & Péruch, 2002; Wilson et al, 1997). For example, Hazen (1982) reported better route

finding by children who had freely explored than those who were led by their parents, suggesting a role for decision-making in route knowledge. Similarly, making decisions about exploratory behavior has also been found to enhance other types of spatial memory (Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011). Thus, whether there is an active advantage in learning weaker forms of spatial knowledge, and the components on which it depends, remain largely unexplored questions.

A third limitation is that the studied environments, both real and virtual, have varied widely in size. There is some evidence that spatial abilities at different scales are partially, although not totally, dissociable (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). The spatial updating literature relies primarily on arrays of objects on a tabletop, path integration research typically covers a few meters, whereas spatial learning research has used room-, building-, or campus-sized environments. The main concern is that small object arrays can be seen simultaneously and spatial updating only requires information about self-rotation, whereas larger, more complex environments cannot be viewed all at once and require more sophisticated path integration to relate objects and views. As a consequence, spatial updating focuses on active movement after learning an object array, while studies in larger environments focus on active movement while learning a spatial layout.

Despite the varying methods, scales, and extents, some common themes emerge. There is evidence that under certain circumstances, rich visual information is sufficient for spatial updating, but is also clear that optic flow alone is not sufficient. Most importantly, all three literatures appear to demonstrate a role for idiothetic information. Presumably, this advantage occurs because spatial updating and path integration depend

on similar mechanisms of self-motion perception, and path integration is important for the acquisition of survey knowledge in larger environments.

Attention and Incidental Spatial Learning

This literature review now focuses more directly on the cognitive dimensions of active spatial learning. It begins by examining the role of attention. This section will investigate what aspects of the environment can be learned passively, without much attentional deployment, and what aspects do require attention. The research reviewed thus far offers little support for a contribution of attention to active spatial learning. In those experiments, however, attention was manipulated by explicitly instructing participants to study the spatial layout or environmental objects. This section reviews two other paradigms in an attempt to clarify the role of attention in spatial learning. First, the literature on intentional and incidental learning is examined, in which attention is manipulated by varying the participant's awareness of an upcoming test, or by employing interference tasks during learning. Second, this section considers research that uses orienting tasks to direct attention more narrowly to specific aspects of the environment. In both cases, these manipulations are examined in regard to acquiring different types of spatial knowledge, including landmark, route, and survey knowledge.

Incidental and Intentional Learning of Spatial Information

Consider the possible effects of the observer's intentions on spatial learning. If learning the environmental layout is facilitated by active attention, then explorers who are informed that they will be tested on the layout and intentionally learn it may perform better than if they are not informed of the upcoming test. On the other hand, if spatial

properties are acquired automatically and learning is incidental, then the awareness of the test should not make a difference.

An early experiment by Lindberg & Garling (1983) investigated whether survey knowledge was automatically encoded as observers were guided on a route through a real environment. Estimates of straight-line distances and directions showed no differences in errors or latencies between intentional and incidental learning groups. However, the incidental group was taken through the route three times while the experimenters pointed out the reference locations. Given these demand characteristics, it seems likely that they may have inferred the purpose of the study and paid attention to spatial information, leading them to perform like the intentional group. In addition, distance and direction estimates improved in both groups with increased exposure to the environment, suggesting an effortful process. The results thus do not support incidental learning of survey knowledge, and may even imply the opposite.

Van Asselen, Fritschy and Postma (2006) investigated the intentional and incidental encoding of route knowledge. Half of their participants were told to pay attention to the route they took through a building because they would be tested on it later. The other half were only told that they needed to go to another room in the building, giving them no reason to pay particular attention to the route. The intentional-encoding group more accurately filled in the route on a map of the building and made fewer errors when reversing the route on foot than the incidental-encoding group. Interestingly, the two groups were equally good at identifying landmarks and putting those landmarks in the correct temporal order. In this case, it appears that learning a route is not an automatic process, whereas acquiring some landmark and ordinal

knowledge may require less effort. In this paradigm, however, it is possible that participants in the incidental-encoding group attended to such environmental properties even without knowledge of the upcoming test, making null results for landmark learning difficult to interpret.

Other evidence from interference tasks suggests that some attention is required to learn even simple elements of a route, such as the sequence of landmarks and landmark-action associations. Albert, Reinitz, Beusmans, & Gopal, (1999) instructed their participants to learn a route from a video display. Those who performed a difficult verbal working memory task while watching the videos were less proficient at putting landmarks in the correct order than those who were allowed to fully attend to the video. The distractor task also interfered with associating landmarks with the appropriate turns on the route, learning the spatial relationships between landmarks, and even associating landmarks with the correct route. Similarly, Anooshian & Siebert (1996) found that intentional learners who performed a visual-imagery task while viewing a route were more likely to make errors in assigning snapshots of scenes to the correct route. These interference tasks appear to affect conscious recollections, not measures of familiarity (Anooshian & Siebert, 1996). Incidental memories may thus provide a sense of being familiar with landmarks, but they are not sufficient to guide the navigator through a route: one may have a sense of having been at a place before, but have no idea which direction to turn or where that place fits into a route or spatial layout.

However, two notes of caution must be sounded before concluding that acquiring the elements of route knowledge requires attention. First, these two studies (Albert et al., 1999; Anooshian & Siebert, 1996) relied on videos to present the routes, so participants

did not have access to the idiothetic information that appears to be important for spatial learning. Second, both reports used distractor tasks, which not only interfere with attention but also place a high demand on working memory. More on the topic of working memory loads will be discussed in the section Working Memory and Spatial Learning.

Incidental encoding of small-scale spatial layouts has also been examined, with mixed results. In children, intentional learning of an object array proves to be no better than incidental learning, suggesting that spatial information may be acquired with little effort (Herman, Kolker, & Shaw, 1982). In adults, alignment effects have also been reported with both intentional and incidental learning of the layout of objects in a room. In the incidental condition, these effects indicate that participants learned the layout from one or two viewpoints, which tend to be aligned with their initial orientation or with the walls of the room (Valiquette et al., 2003). Explicit instructions to intentionally learn the layout also lead to alignment with the walls of the room. Strong reference axes may influence both intentional and incidental learning of a layout (Mou & McNamara, 2002).

On the other hand, intentional learning appears to improve performance when the task is to reproduce the layout by placing the objects on a table immediately after viewing, rather than to make spatial judgments from imagined positions (Rodrigues & Marques, 2006). When the reproduction task is delayed for several minutes, the performance of the incidental group suffers, while the intentional group remains fairly accurate. Participants in incidental and intentional conditions also appear to have different memorization strategies: intentional learners focused on the locations of the objects, whereas incidental learners tried to remember the object names. These results

suggest that spatial information can be learned briefly when attention is focused elsewhere, but cannot be retained over time.

Intentional learning may be based on associative-reinforcement mechanisms, whereas incidental learning can occur without reinforcement. Reinforcement learning “blocks” or “overshadows” later learning, so learning a new piece of information interferes with future learning. In contrast, incidental learning does not act as a blocker, and thus does not prevent future learning. Doeller & Burgess (2008; Doeller, King, & Burgess, 2008) observed blocking when people perform tasks that emphasize learning the relationship between objects and a landmark, but not when the tasks emphasize learning the relationship between objects and an environmental boundary. These findings imply that spatial relations among landmarks must be intentionally encoded, whereas spatial relations with boundaries are learned incidentally. Thus, not only do local features, like landmarks, help in learning a layout, but intentional processing of those relations among features leads to greater spatial learning. Global environmental features, such as boundaries, are not explicitly “associated” with object locations, but appear to be acquired more automatically.

Before concluding, it should be noted that even without explicit instructions to attend to the spatial environment, participants in these studies may still allocate attention to the spatial layout. They may be inherently inclined to attend to spatial properties, or the demand characteristics of the experiment may lead them to do so. Acknowledging such concerns, these studies suggest that explorers learn limited properties of landmarks and routes incidentally, without explicit attention. However, full route knowledge and survey knowledge appear to require the intention to learn, implying the need for attention

to the relevant spatial relations. Specifically, incidental encoding allows the observer to identify landmarks, their relation to boundaries, and in some cases their sequential order, although there is conflicting evidence on this point. On the other hand, intentional encoding appears to be necessary for place-action associations, reproducing a route, and spatial relations between landmarks. For small-scale spatial layouts that do not require as much exploration and integration, there appears to be little difference between incidental and intentional learning, although the latter may lead to more long-term retention.

Differential Attention to Environmental Properties

Another paradigm for investigating the role of attention in spatial learning is to manipulate the prior information or the orienting task that is presented to the participant. These manipulations aim to direct attention to particular aspects of the environment, and appear to influence whether places, sequences of landmarks, routes, or survey knowledge are acquired during learning. This strategy assumes that some attention is actively allocated, but only to specific aspects of the environment.

The type of information about the environment that is presented prior to learning can push participants toward encoding particular aspects of the layout. For example, Magliano, Cohen, Allen, & Rodrigue (1995) gave their participants information on the landmarks, route, or overall layout before viewing a slideshow of a route, with instructions to learn that information. All groups were able to recognize landmarks from the route and to put landmarks in their correct temporal order. In survey tasks, the controls who received no additional information performed better than those given landmark information, indicating that there is a cost associated with being given information that is inappropriate for a survey task. Despite being able to put landmarks

in sequential order, the control and landmark groups performed poorly when asked to give directions for the route, indicating that they did not associate actions with particular landmarks. These results are consistent with findings discussed earlier (e.g. Magliano et al., 1995; van Asselen et al., 2006) that some landmark and ordinal knowledge is acquired without much effort, but that full route and survey knowledge requires attention, additional information, or active manipulation of that information.

Directing attention to different features of the environment by manipulating the orienting task during learning can also influence the type of spatial knowledge that is acquired. For example, when instructed to only learn locations in the environment, participants encode sequences of landmarks without much effort but appear to have difficulty placing landmarks in context, including the appropriate action to take at a landmark and the spatial relations among landmarks, suggesting a potential dissociation between place knowledge on the one hand and route and survey knowledge on the other (e.g. Albert et al., 1999; Magliano et al., 1995; van Asselen et al., 2006). However, attention to landmarks at the expense of turns while learning a route can also impair the ability to put landmarks in sequential order, particularly in older adults (Lipman, 1991). Tracking a particular landmark over time also adversely affects the acquisition of survey knowledge, as tested by placing locations on a map that contains two given reference points (Rossano & Reardon, 1999). This task led participants to encode locations with respect to the tracked landmark at the expense of accurately encoding them with respect to each other.

To compare learning of places and actions, Anoshian (1996) guided participants along a route that contained simulated landmarks (photographs of e.g. a fire station),

while instructing them either to anticipate place names or learn turns on the route. For the place group, the landmarks were visible on the first walk through the route, but covered on the three subsequent walks, and participants were tested on their memory for the location each time. For the turn group, the landmarks were visible each time through the route, and participants were tested on what action they needed to take at each landmark. Interestingly, the place group was not only better at later recalling landmarks as they walked the route, but also better at naming the next landmark in the sequence and pointing to landmarks from new positions. While this result might seem surprising, the orienting task required the place group to learn the upcoming landmark at the next location, so they acquired the landmark sequence and apparently some configurational knowledge. In contrast, the action group simply had to associate the current landmark with an action, without anticipating the next landmark. These results suggest that attending to the sequence of places on a route (with idiothetic information) can lead to greater survey knowledge than attending to place-action associations, the basis of route knowledge.

Other evidence also indicates that the orienting task can influence whether route knowledge or survey knowledge is acquired. For instance, day-to-day use of a building typically involves repeatedly traversing a few familiar routes. Moeser (1988) found that nurses who worked in a complex hospital building did not acquire survey knowledge of the building even after two years of experience. This finding suggests that the daily task of following known routes does not inexorably lead to survey knowledge, contrary to Siegel & White's (1975) well-known hypothesis that landmark knowledge is learned first, followed by routes, and eventually survey knowledge emerges. In contrast, Taylor

et al. (1999) found that experimentally manipulating the orienting task influences the spatial knowledge that is acquired. Participants given the goal of exploring a complex building to learn the quickest routes through it were better on later tests of route knowledge than those instructed to learn the building's layout. However, the opposite effect was not observed in this case: two groups performed equally on tests of survey knowledge, presumably because the route-learning group had explored the building widely to find efficient routes. Finally, participants who learned the building by studying a map tended to show an advantage on both route and survey tests over those who learned it by walking in the environment (see also Thorndyke & Hayes-Roth, 1982, for comparisons of map and route learning without orienting tasks).

There also appear to be important individual differences in learning survey, as well as route, knowledge (Wolbers & Hegarty, 2010). After 24 participants were driven through two connected routes, Ishikawa & Montello (2006) found that 17% of them had relatively accurate survey knowledge after one exposure, and only another 25% achieved accurate survey knowledge after ten exposures (where "accurate" is rather liberally defined as absolute pointing error less than 30 deg). Only half of the participants improved their survey knowledge over time, again contrary to Siegel and White's (1975) hypothesis.

Older adults appear to have difficulty retracing a route (Wilkniss, Jones, Korol, Gold, & Manning, 1997), putting scenes from the route in the correct order, and selecting the most informative landmarks for navigation (Lipman, 1991). Rather than paying attention to landmarks that are relevant to finding the route, they appear to attend to those that are most perceptually salient. Likewise, children tend to select highly noticeable but

spatially uninformative landmarks (Allen, Kirasic, Siegel, & Herman, 1979). They are, however, able to navigate the route well when given helpful landmarks. These results indicate that the ability to navigate a route successfully is related to the ability to attend to relevant landmarks and not be distracted by other salient objects. Verbal information about landmarks at decision points has proven to be most informative when following a route (Denis, Pazzaglia, Cornoldi, & Bertolo, 1999), suggesting that attention to and selection of informative landmarks is crucial to successful route navigation.

In sum, while certain environmental features may be learned automatically, the evidence indicates that acquiring route and survey knowledge depends on the intention to learn or the orienting task, and by implication, the deployment of attention. Rather than progressing through a regular sequence of place, route, and survey knowledge, the type of spatial knowledge that is acquired depends on the task demands during learning.

Landmarks, landmark-boundary relations, and to some extent sequences of landmarks appear to be acquired incidentally, regardless of the task. In contrast, the selection of informative landmarks, place-action associations, and spatial relations among landmarks appear to depend on tasks that direct active attention to the corresponding environmental properties. Given that metric survey knowledge also depends on the presence of idiothetic information during learning, this may explain the failure to find reliable effects of attention in desktop VR (see section on Idiothetic Information During Walking). Thus, the present findings indicate that the control of attention, in combination with idiothetic information, is an important component of active exploration.

There are still many open questions involving attention and spatial learning. Attention may interact with the other components of active exploration by, for example,

modulating the contribution of idiothetic information or playing a mediating role for cognitive decision-making. The implications of such possible interactions have yet to be studied. In addition, the limits of spatial attention have not been investigated. It may be possible to learn multiple aspects of the environment when directed to attend to both route and survey information. On the other hand, there may be a limit to attentional capacity that leads to depressed performance on both.

Given that attention influences the acquisition of route and survey knowledge, this implies that the relevant spatial information must be encoded in working memory. Thus, the role of working memory in spatial learning is addressed next.

Working Memory and Spatial Learning

Attention appears to contribute to the encoding of certain aspects of the environment, but it remains to be seen how that encoding takes place. Some environmental information can be encoded without a major investment of attention, such as landmarks and landmark sequences, but other information may be difficult to encode even with full attentional resources, such as metric spatial relations. Thus, this section discusses the role that particular components of working memory play in encoding different types of spatial information. Working memory may be considered a part of active learning, especially when active manipulation or transformation of the spatial information is required. Working memory also affects how and where attention is allocated. As seen with attention, working memory appears to contribute to spatial learning in a variety of ways, depending on the component of working memory involved,

the particular spatial information, and whether the information is actively transformed or is simply maintained.

The Interference Paradigm

The main experimental framework in the literature on working memory is an interference paradigm, in which distracter tasks designed to interfere with specific working memory processes are used to investigate how different spatial properties are encoded. It is thus important to distinguish two factors: (a) the aspect of the environment that is to be encoded and (b) the type of working memory process involved. The former refers to the information that is to be acquired by the observer, such as landmark information, route knowledge, or survey knowledge. The latter refers to whether that information is encoded via verbal, visual, or spatial working memory, or some combination thereof. Distracter tasks are designed to interfere with one or more of these functional processes during the learning phase. The resulting knowledge of the environment is probed during the test phase, although distracters can also be used to interfere with retrieval of information at test. The disruption of one type of encoding may thus impair the acquisition of a particular environmental property but not others, revealing something about how they are encoded. For example, a spatial interference task may inhibit the encoding of survey knowledge without disrupting the acquisition of route knowledge. This section aims to identify such relationships between types of working memory and forms of environmental knowledge.

It should be clear at the outset that the understanding of working memory continues to develop, and this review is not committed to a particular framework. The goal is merely to use current theory to see if it yields insights into spatial learning.

Working memory is typically broken down into multiple functional subunits (Baddeley, 2003; Logie, 1995). These are thought to include verbal and visual-spatial working memory, where the latter includes visual and spatial components. In addition, the spatial component is often divided into sequential and simultaneous processes, which appear to be independent of each other (Pazzaglia & Cornoldi, 1999). Researchers often test visual-spatial working memory using the Corsi block test (Pazzaglia & Cornoldi, 1999; Zimmer, 2008). Beginning with a random layout of blocks, the experimenter points to a sequence of blocks, and the participant must then repeat the sequence. This task contains a high degree of sequential information; the participant must not only tap the appropriate blocks, but also do so in the correct order. Thus, this particular test of visual-spatial abilities involves both spatial and sequential aspects of working memory. Verbal working memory might also play a role in acquiring spatial information if the participant encodes a route using verbal directions, for example, or if spatial information is presented in the form of text. A verbal interference task may probe the degree to which an observer verbally encodes spatial information.

As discussed in the section Incidental and Intentional Learning of Spatial Information, secondary tasks do not appear to interfere with the encoding of certain types of information, such as places or landmarks. On the other hand, both verbal and visual-spatial interference tasks disrupt the encoding of route information, including assigning landmarks to the correct route and putting them in sequential order, as well as learning spatial relationships (Albert et al., 1999; Anooshian & Seibert, 1996), and may also distract from path integration (Tcheang et al., 2011). Similarly, a verbal shadowing task impairs selecting scenes from a route, making relative distance judgments, and verifying

the route on a map (Allen & Willenborg, 1998). These results indicate that people use some sort of verbal strategy to help encode route information when passively watching a video or slides. However, it is less clear whether this is the case when actively exploring the environment.

Encoding Spatial Texts

An important limitation of the literature on working memory in navigation is that the majority of research has used spatial descriptions as stimuli. Although such studies may illuminate learning from directions or other verbal descriptions, they are less informative about ordinary spatial learning from exposure to the environment. Just as with desktop VR, the spatial text paradigm is likely to be supplanted by more immersive studies as they become available. However, given the dearth of working memory research in which participants are immersed in a real or virtual environment, studies using spatial text currently provide some of the only evidence on working memory and spatial learning. One point of contact is that both spatial text and route learning tap into the sequential aspects of spatial working memory. Most spatial descriptions proceed through a route and avoid cumbersome descriptions of distance and orientation relationships. Similarly, much immersive spatial learning is achieved by traversing routes from place to place, so spatial descriptions may bear some similarity to route learning.

Visual-spatial working memory appears to be key for learning spatial texts (De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Gyselinck, De Beni, Pazzaglia, Meneghetti, & Mondoloni, 2007; Gyselinck, Meneghetti, De Beni, & Pazzaglia, 2009), especially during encoding (Pazzaglia, De Beni, and Meneghetti, 2007). While

concurrent verbal tasks disrupt spatial texts, concurrent spatial tasks disrupt spatial texts more than verbal tasks do (Pazzaglia et al., 2007). Concurrent spatial tasks interfere during both encoding and retrieval (Pazzaglia et al., 2007), while measures designed to interfere with central executive processing interfere with encoding only (Brunyé & Taylor, 2008). Thus, it appears likely that verbal and executive functions are involved with encoding spatial memories from texts, but visual-spatial working memory plays a larger role in both encoding and retrieving spatial descriptions.

Deeper understanding of the relationship between working memory and spatial learning comes from investigating the subunits of visual-spatial working memory. In order to distinguish the various components, Pazzaglia & Cornoldi (1999) created four different interference tasks, designed to probe verbal, visual, spatial-sequential, or spatial-simultaneous aspects of working memory during encoding of four types of texts. They found that spatial-sequential working memory contributes the most to learning sequential information, while verbal encoding plays a role in learning spatial-simultaneous information, possibly indicating that participants are verbalizing the simultaneous information. Pazzaglia and Cornoldi (1999) then investigated how the same three visual-spatial distracters interfered with the encoding of texts that emphasized route, survey, or visual knowledge of the environment. The authors expected that, if such information is encoded via separable sub-systems of visual-spatial memory, the interference tasks would interfere with the corresponding spatial information. The results show that the sequential task indeed impaired recall of the route description, but also interfered with the survey and visual texts. This finding could be due to the inherently sequential nature of verbal descriptions: spatial information in the texts was presented serially. It thus appears that

spatial-sequential interference disrupts the encoding of both route and survey information from text, in contrast to spatial-simultaneous memory, which did not interfere with any spatial information. However, it is possible that this effect is attributable to the sequential nature of texts, or that the spatial-simultaneous task may have been too easy to produce comparable interference.

The results for maps complement those for texts. Coluccia, Bosco, and Brandimonte (2007) asked participants to perform two types of interference tasks while studying a map, and then to draw a sketchmap of locations and roads. They found that tapping a spatial pattern interfered with learning both route and survey knowledge, while a verbal interference task did not affect either one. However, as we will see, other evidence suggests that verbal tasks do interfere somewhat with acquiring route knowledge in the real world when the route is experienced sequentially (Garden, Cornoldi, & Logie, 2002). Displaying the spatial layout simultaneously allows participants to encode survey and route information via spatial-simultaneous working memory, whereas presenting visual or textual information sequentially invokes verbal and spatial-sequential working memory to encode route and survey knowledge.

In sum, there appear to be multiple components of working memory involved in encoding spatial information from textual descriptions. First, verbal working memory appears to play a role in encoding route information that is presented sequentially in text. Second, spatial working memory is also involved when spatial information is described in text. However, based on this evidence, it is difficult to conclude that spatial-sequential working memory is normally invoked when encoding route and survey knowledge, because textual stimuli are inherently sequential. For the same reason, one cannot infer

that spatial-simultaneous working memory is normally uninvolved in the acquisition of route and survey knowledge; it is clearly involved when such information is presented simultaneously in the form of a visual map.

Working Memory During Immersive Spatial Learning

Let us turn to the few studies that have investigated working memory during “eye-level wayfinding,” or immersive spatial learning in a real or virtual environment. As previously observed with slide and video sequences (Albert et al., 1999; Allen & Willenborg, 1998; Anooshian & Seibert, 1996), these studies confirm that verbal encoding plays a role in the acquisition of route knowledge. Participants who learn a route by viewing a display of a virtual environment (Meilinger, Knauff, & Bühlhoff, 2008) or by walking through an actual town (Garden et al., 2002) while performing a secondary lexical decision task make errors on subsequent attempts to follow the same route. Ordinal information for a route might be verbally encoded as a series of place names with associated left or right turns. Given the ample research on dual coding of information, it may not be surprising that a route may be encoded verbally as well as visuo-spatially (Meilinger et al., 2008).

Regarding spatial interference with route learning, at first glance the results for immersive learning seem to contradict those for spatial texts. Pazzaglia & Cornoldi (1999) reported that a sequential spatial task interfered with route learning from text, whereas a simultaneous spatial task did not. In contrast, both Garden et al. (2002) and Meilinger, et al. (2008) found that a spatial distracter interfered with route learning in an immersive environment. However, Garden et al.’s (2002) interference task called for participants to tap a spatial pattern in a particular order; this can be considered a

sequential spatial task, so is consistent with Pazzaglia & Cornoldi's (1999) results. But the auditory interference task used by Meilinger et al. (2008) required participants to identify the direction from which a sound was coming—a simultaneous spatial task, which nonetheless interfered with route learning. This apparent inconsistency may be reconciled in the following way. The auditory spatial task required participants to respond to tones to their left, right, or front by pressing one of three buttons, and thus the spatial direction of the tone might have been verbally encoded. Given that verbal distracters interfere with route learning, this distracter task may have also done so. This general pattern of results points to a role for both verbal working memory and spatial-sequential working memory in the encoding of route knowledge.

Mental Manipulation of Spatial Information

Returning to the theme of active and passive spatial learning, a distinction has recently been introduced between active and passive working memory tasks (Bosco, Longoni, & Vecchi, 2004). Passive tasks involve memorizing spatial information, while active tasks require manipulation or transformation of that information. An example of a simultaneous active task is one in which participants must solve a jigsaw puzzle by reporting the number of the correct piece without actually moving the pieces, thus requiring mental rotation and comparison. On the other hand, the Corsi block task, in which participants must repeat a sequence of blocks, is a sequential passive task. Bosco et al., (2004) found that performance on both of these tasks correlates with the ability to learn landmark, route, and survey knowledge from studying a map, as measured respectively by landmark recognition tasks, route recognition and wayfinding tasks, and map completion and distance judgments. This correlation with both active and passive

tasks holds especially for men, while active tasks were better predictors of women's spatial learning abilities. In addition, when learning an environment from a map, both active and passive simultaneous working memory ability was related to survey knowledge of landmark locations and road connections (Coluccia et al., 2007). This result is not surprising, however, because a map provides simultaneous information about the layout. Thus, active manipulation in working memory does not appear to make a strong contribution to active spatial learning, but it does deserve further investigation in light of the observed gender difference.

The tasks considered so far have been designed to interfere with elements of working memory to test their role in spatial learning. Alternatively, one might approach the same question by investigating whether specific active working memory tasks facilitate aspects of spatial learning. For example, instructions conducive to mental imagery, such as imagining oneself in the environment described in a spatial text, have been shown to improve performance on a sentence verification task more than just repeating the previous sentence in the text (Gyselinck et al., 2007; Gyselinck et al., 2009). This finding seems to be consistent with enhancement by active as opposed to passive working memory tasks.

Few studies have directly tested whether learning is enhanced by active manipulation of spatial knowledge. It is known that giving people advanced information such as a map or the route they will encounter improves learning (e.g. Magliano et al., 1995). Münzer, Zimmer, Schwalm, Baus, & Aslan (2006) found that participants who actively used a map to follow a route in a real environment were better at retracing the route and placing landmarks than those who viewed the route on a map and then received

visual or auditory instructions about which way to turn. The first group had to interact with the environment to figure out the turns, requiring them to manipulate spatial information in working memory. This type of mental manipulation might contribute to an active advantage in spatial learning. Active mental manipulation may also interact with the other cognitive components of active navigation outlined in the introduction: making navigational decisions and allocation of attention.

In sum, the existing evidence suggests that different elements of working memory may be involved in particular aspects of spatial learning. A consistent result is that verbal working memory seems to play a role in encoding route information, whether it is presented via text, slide sequences, passive VR, or walking with idiothetic information. Similarly, spatial-sequential working memory also appears to contribute to the encoding of route knowledge from both text and VR displays. However, the relationship between the components of working memory and the acquisition of survey knowledge is unknown, due to a dearth of pertinent research. Most existing experiments are based on spatial descriptions that present survey information sequentially, and thus not surprisingly invoke spatial-sequential working memory; analogously, spatial-simultaneous working memory is invoked when encoding survey knowledge from a map. Systematic exploration of working memory components in survey learning during walking in immersive environments is needed. Finally, the distinction between active manipulation and passive storage of spatial information in working memory opens up a potential avenue for research. Initial results suggest that mental manipulation of spatial information may contribute to active learning of both route and survey knowledge, but more work with immersive spatial learning is called for.

Conclusions

The intuition that drivers acquire greater knowledge than passengers (Appleyard, 1970) raised a number of questions about active and passive contributions to spatial learning to which, despite the limitations of the existing literature, some preliminary answers can be offered.

First, consistent with the first hypothesis, idiothetic information contributes to spatial updating in small-scale environments, to path integration in large-scale environments, and to spatial learning of survey knowledge. It may require a sufficiently complex path or repeated exposure for idiothetic information to reveal its effect, and several studies did not control for field of view and free head movements. Nevertheless, a core set of findings demonstrates an influence of idiothetic information on spatial learning. Motor and proprioceptive information, and perhaps vestibular information, appear to play a role, although their relative contributions remain to be determined. This conclusion is consistent with the theoretical claim that survey knowledge is derived from information about metric distances and turn angles along a traversed route – the sort of information provided by idiothetic systems. There is preliminary evidence that motor and proprioceptive information also contribute to route knowledge, perhaps by better specifying the action (turn angle and distance) in each place-action association. The role of idiothetic information in acquiring weaker topological and ordinal knowledge remains to be investigated.

Second, seemingly at variance with the second hypothesis, there is little evidence that making decisions about one's path during exploration, in the absence of idiothetic

information, contributes to spatial learning. Any effects of choosing a route, as opposed to following a prescribed route, are small, unreliable, and vulnerable to minor procedural differences. However, research on this topic has only tested the acquisition of survey knowledge in desktop VR, so it is not surprising that performance is poor. Thus, the hypothesis that decision-making is sufficient for route learning remains to be tested. It also remains possible that decision-making contributes to survey learning in combination with idiothetic information, but this question must be investigated during walking in real or virtual environments, and has not yet been satisfactorily examined.

Third, consistent with the third hypothesis, the allocation of attention to relevant environmental properties contributes to the acquisition of route and survey knowledge. Whereas landmarks, their relation to boundaries, and possibly landmark sequences appear to be encoded incidentally, landmark-action associations and spatial relations among landmarks require the intention to learn, implicating attention. Directing attention to place-action associations facilitates route learning at the expense of survey learning, whereas directing attention to configural relations facilitates survey knowledge but may not impact route knowledge. It is important to note that research in desktop VR has produced little evidence that attention to layout, as opposed to objects, influences survey learning. The absence of idiothetic information in desktop VR may have masked the contribution of attention, making the presence of idiothetic information necessary to test the contribution of attention to the acquisition of survey knowledge. It is also unclear how attention interacts with cognitive decision-making. It is possible that making decisions about exploration yields sufficient attention for route or survey learning, or that additional orienting of attention could aid in spatial learning.

Finally, spatial learning is influenced by the information that is encoded in working memory. The interference paradigm has provided evidence that verbal and spatial-sequential working memory are involved in route learning, regardless of whether the mode of presentation of route information is verbal or eye-level visual. In contrast, spatial-simultaneous working memory is implicated in the encoding of survey knowledge from visual maps, but otherwise the working memory components involved in survey learning are unknown. Further research based on ambulatory environments, rather than spatial texts, are needed for progress in this area. In addition, some promising results suggest that active manipulation of spatial information in working memory may enhance spatial learning.

In sum, there appears to be a reliable active advantage in spatial learning, such that it is task-dependent. Walking humans acquire place, landmark, route, and/or survey knowledge depending on their goals, and can modulate their learning by attending to and encoding different environmental properties. A complex navigation task may tap into some subset of this knowledge, depending on the goals of the navigator. Such spatial learning involves many cognitive processes that interact to varying degrees depending on the task, on the deployment of attention and working memory, and active mental manipulation of spatial information.

However, many questions remain about the components of active learning in spatial navigation. For one, the underlying neural bases of active and passive spatial learning are relatively unexplored. Although there is a large body of work on the neural correlates of landmark, route, and survey learning (Chrastil, under review), there is little research that directly addresses the correlates of active and passive learning in humans. One major

obstacle is that physical movement is severely restricted by most neuroimaging techniques, whereas work in full ambulatory environments is needed to understand the contributions of decision making and attention. Imaging studies may still inform our understanding of non-motor active learning, but their limitations must also be acknowledged.

In light of the many unanswered questions, the tentative conclusions presented here must be tested in a more rigorous and systematic fashion in ambulatory environments with full idiothetic information. In particular, it is critical to determine whether influences of decision-making and attention are dependent on the presence of idiothetic information during learning for both route and survey knowledge. The interaction between the factors of idiothetic information, decision-making, and attention has been largely ignored in previous research. The remainder of this dissertation is devoted to answering these outstanding questions. Chapter 3 focuses on the interaction between proprioceptive information, vestibular input, and decision making in survey learning. Chapter 4 examines these same factors in a graph knowledge task. Finally, Chapter 5 looks more closely at the question of attention by orienting participants' attention to different aspects of the environment. The three experimental chapters will also consider the role of individual differences in spatial learning, which have not often been examined in conjunction with questions of active and passive navigation. These three chapters provide a comprehensive and systematic test of the contributions of the components of active navigation.

Despite these gaps, the groundwork has been laid for a better understanding of active and passive spatial learning. Idiothetic information during active walking is important

for the acquisition of metric survey knowledge. Active attention selects landmark sequence, route, or survey information to be encoded in the relevant units of working memory. For a more comprehensive picture of spatial learning, the systems in this interconnected network must be considered in relation to one another as they work together in complex navigation tasks.

Chapter 3

Experiment 1: Active and Passive Learning in a Test of Survey Knowledge

Introduction

Survey knowledge is the most metrically accurate form of spatial knowledge. Accurate survey knowledge is like a Euclidean map, with correct distances and angles between locations. A person with survey knowledge not only knows how two locations are spatially related to each other, that person also understands where those locations are positioned within the larger environment. Not surprisingly, human survey knowledge is often not very accurate, and can be highly variable, both within and between individuals. The purpose of Experiment 1 is to test the contributions of visual, vestibular, and proprioceptive information, and the contribution of decision-making to survey knowledge.

Survey knowledge is the form of spatial learning that has been most studied in previous literature on active and passive navigation. In particular, the role of information has been examined, although with somewhat mixed results. As laid out in the introduction, there are several possible sources of information that a navigator could use to build survey knowledge: vision, vestibular input, motor efference, and proprioception. Some research suggests that both proprioception and vestibular information are very important to learning survey information (e.g. Chance et al., 1998; Waller et al., 2004), while others find that idiothetic information contributes little beyond vision alone (Waller & Greenauer, 2007; Mellet et al., 2010). Interestingly, the size and complexity of the environment may interact with information, such that smaller and simpler environments may be learned relatively well without idiothetic information. Idiothetic information may contribute more in large or complex environments. For example, Ruddle et al. (2011a) found an advantage for physically walking—either on a linear or omni-directional

treadmill—over purely visual exploration, but only in a large environment. Idiothetic information may be noisy in small environments, and thus may not make a significant contribution beyond vision. However, with significant translation or rotation from large or complex environments, visual path integration could become less accurate, and the contribution of idiothetic information may become clear.

In contrast to the role of information, there has been very little examination of the role of cognitive decision-making in the acquisition of survey knowledge. One recent study of path integration showed that those who made decisions about their outbound path had no better performance than those who were led on an outbound path (Wan et al., 2010). However, the paths in that experiment were very simple, which might not reveal a contribution of decision-making. In addition, path choice in path integration may be very different from choosing how and where to explore a more complex environment, and so those results may not be applicable here. Others who have tested the effects of decision-making have used desktop VR (e.g. Péruch et al., 1995; Wilson et al., 1997), which neglects many of the effects of idiothetic information. Previous research that included idiothetic information often guided participants through a set route, neglecting the role of decision-making, which might have affected how participants learn the environment. This variety of methodologies makes it difficult to compare across studies to determine whether the level of information or the task instructions are critical to survey learning. Thus, previous studies have not independently manipulated information and decision-making when considering survey knowledge.

There are several gaps in the literature that Experiment 1 specifically tests. First, a direct examination of the contribution of decision-making is needed. Second, the role

of information needs to be examined more systematically, considering the mixed results from previous research. Finally, few of the experiments on survey learning have examined the role of individual differences, which may play a large role in survey learning. Experiment 1 fully crossed three levels of information—Walk, Wheelchair, and Video—with two levels of decision-making—Free and Guided—during exploration of a complex maze environment. Walking groups had full access to all idiothetic and visual information, the Wheelchair groups had access to vestibular and visual information, and the Video groups had access to vision alone. The Free groups were allowed to make decisions about where they moved during exploration, while the Guided groups were guided along paths matched to the Free Walking group. Thus, decision-making was tested at all levels of information, and vice versa.

Based on previous findings and theoretical considerations, several predictions can be made. Idiothetic information, particularly proprioceptive and motor input, should prove to be a significant contributor to build up metric survey information. Visual information may be sufficient for relative placement—for example, that one object is to the left of another object—but idiothetic information could significantly contribute to the acquisition of the absolute distances and angles necessary for metric survey knowledge. The size and complexity of the environment may be important factors in revealing the contribution of idiothetic information. The environment used here was fairly complex, but was also somewhat smaller than some of the environments used in previous research (e.g. Ruddle et al., 2011a; Waller et al., 2003; Waller et al., 2004), which were on the scale of city blocks. Given the complexity of the space, the contribution of idiothetic information should be revealed. Idiothetic information may aid survey knowledge

because proprioception/motor and vestibular input specify distances and angles during active walking. Thus, it is expected that walking during the learning phase will yield better performance on the shortcut test than watching a video. The contribution of decision-making is less clear. It may be possible that the contribution of decision-making will interact with information, such that any contribution of decisions would only be observed under conditions of full idiothetic information.

The results of Experiment 1 suggest that idiothetic information makes a significant contribution to learning survey knowledge. Participants who walked during exploration had smaller errors and were more consistent in their responses than those who explored in a wheelchair or by watching videos. In contrast, making decisions about exploration offers no benefit to survey learning. Large individual differences were observed in all groups, and several measures were identified that predicted performance in the shortcut test.

Methods

Participants

Participants were recruited through advertisements and were paid for their time at the rate of \$8-10/hour. All participants signed forms indicating their informed consent to be a part of the study in fulfillment of the requirements of the Brown University IRB. 134 (67 female) people participated in the experiment. 15 (9 female) withdrew due to symptoms of simulator sickness, and 7 (2 female) for failure to find all of the objects during exploration. 112 participants (56 female) completed the experiment. Mean age of participants who completed the study was 21.63 (SD 4.11). The rates of dropout due to simulator sickness for the different groups were: Free Walk, 5 (plus 1 failure to find all

the objects); Guided Walk, 1; Free Wheelchair, 0 (plus 4 failures to find all the objects); Guided Wheelchair, 1; Free Video, 8 (plus 2 failures to find all the objects); Guided Video, 0.

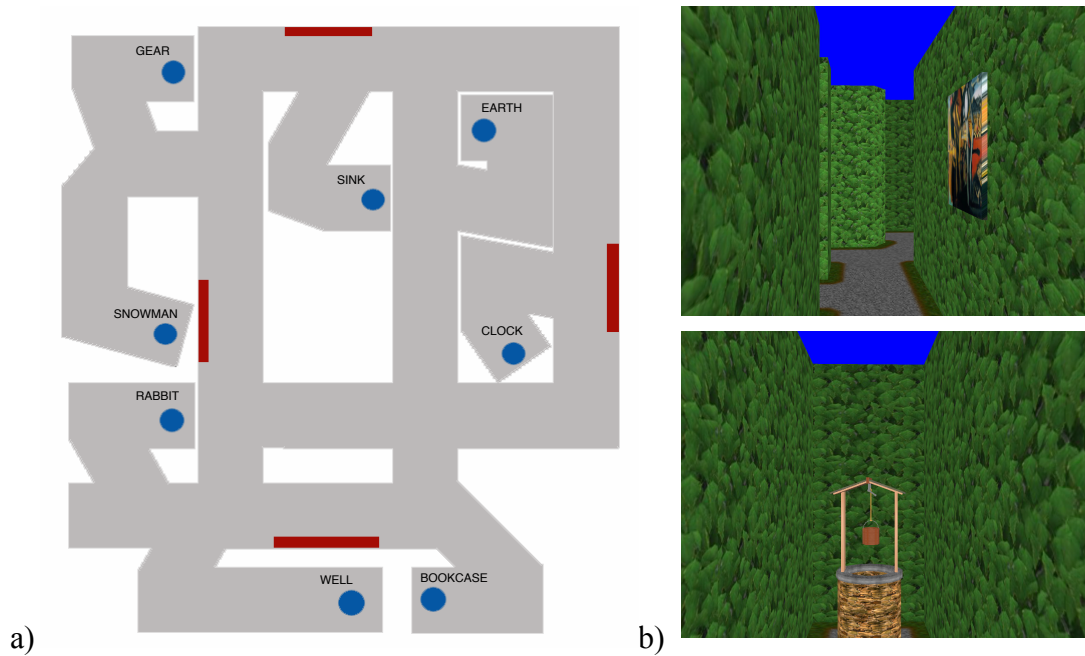


Figure 1. a) Outline of the maze used in all of the experiments. The maze included eight objects (blue circles, clockwise from lower right): bookcase, well, rabbit, snowman, gear, sink, earth, clock. There were also four paintings (red rectangles) in the hallways that acted as landmarks. Participants 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.

Equipment

This experiment took place in the VENLab, a 12m x 12m ambulatory virtual reality setup. Images were presented to the participants using a Rockwell-Collins SR80A head-mounted display (HMD) with a 63° horizontal x 53° vertical field of view and resolution of 1280 x 1024 pixels. Participant head position and orientation was tracked and recorded using an InterSense IS900 tracking system with a 50 ms latency and spatial resolution of 1.5mm/0.10°. Participants made responses with a USB radio mouse and by walking to target locations. Images were generated on a graphics PC using Vizard

(WorldViz) to render the images. Naturalistic noise was presented to the participants over headphones to prevent participants from receiving information about their location or orientation in the room from auditory cues.

Environment

This experiment used a virtual maze environment during both the learning and test phases (Figure 1). The maze contained eight objects, all of which were located at the ends of branch hallways, and were not visible from the main corridors. The objects were common items, such as a sink or bookcase, all of which had been scaled to be easily visible at eye height. In the maze, there were also four paintings, which served as landmarks. These landmarks were hung on the walls of the maze in some of the main corridors to assist participants as they oriented themselves during exploration.

		DECISIONS	
		Yes	No
INFORMATION	Visual + Idiothetic	Free Walk	Guided Walk
	Visual + Vestibular	Free Wheelchair	Guided Wheelchair
	Visual	Free Video	Guided Video

Table 1. Design of Experiments 1 and 2

Design

The design of the experiment involved 6 groups of participants in a 3 x 2 design, with three levels of information (Walk, Wheelchair, Video) and two levels of decision-making (Free, Guided), yielding 6 learning conditions: (i) Free Walking, (ii) Guided Walking, (iii) Free Wheelchair, (iv) Guided Wheelchair, (v) Free Video, and (vi) Guided Video. Each group consisted of 16 participants, randomly assigned with the restriction that the groups were evenly divided between males and females, for a total of 96

participants in this experiment. Eight additional participants were added to two of the groups (Free Walking and Free Video), for a grand total of 112 participants.

Learning Phase

(i) Free Walking: Using a fully immersive VR setup, the Free Walking group of participants were instructed to freely explore the environment, providing them with all normally available information, including visual, motor/proprioceptive, vestibular, attention, and decisions (see Table 1). This free exploration in the virtual maze lasted 10 minutes, with each participant starting at one of 6 locations. (ii) Guided Walking: Participants in the Guided Walking group were guided along the same paths as the Free Walking group, giving them all of the idiothetic information, but removing the decision-making component. Using matched paths ensured that participants received the same exposure to the maze as their counterparts in the Free Walking condition. (iii) Free Wheelchair: In the Free Wheelchair condition, participants were pushed through the maze in a wheelchair by the experimenter, minimizing motor/proprioceptive information. Vestibular information was retained, although some characteristics of the vestibular information, such as the pattern of acceleration, were different from walking. The Free Wheelchair group indicated to the experimenter which direction they want to turn by pressing buttons on a tablet PC, which then played a sound file to the experimenter through headphones. The experimenter then pushed the wheelchair in the direction indicated by the participant. (iv) Guided Wheelchair: In the Guided Wheelchair condition, participants were wheeled in the maze, matching the paths to the Free Walking group. (v) Free Video: Finally, vestibular input was removed, leaving only visual information in the Video groups. The Free Video groups pressed buttons to move around

a desktop VR setup. (vi) Guided Video: The Guided Video groups simply watched the exploration video from the Free Walking groups. Table 1 shows the information available to participants in all exploration groups. The paths in the Guided Wheelchair condition could potentially have been matched to either the Free Explore or Free Wheelchair condition, depending on the input of interest. Likewise, the Guided Video could have been matched to either the Free Walking or Free Video groups. The primary motivation for Experiment 1 was to investigate the contribution of idiothetic information, and so all groups were compared to the Free Walking group.

The paths from the Free Walking, Free Wheelchair, and Free Video groups could not be matched, since participants in those conditions were allowed to make decisions about how to explore. Thus, differences between these groups may be attributable to the experimental manipulations or to the differences in exploration paths. In order to match the paths in the Free conditions as much as possible, measures were taken during exploration in the Free Walk condition and used to govern the Free Wheelchair and Free Video conditions. For instance, the speed with which the participants were wheeled in the environment and the speed of the video keyboard controls were matched to average Free Walk speed. Paths were also analyzed to determine whether there were significant differences in exploration parameters between these conditions, such as the total path length or the number of objects visited.

Test Phase

Survey knowledge was tested through a shortcut task in which the participant walked directly from a starting object to a target object. Each trial began with the participant entering a branch hallway of the maze containing the starting object

(approximately 1 meter from the object), to allow them to orient themselves. Starting the trial at the location of an object prevented the participant from exploring the maze and gaining additional knowledge during the test phase. The participant was then directed to walk into the starting object. At that point, all objects, landmarks, and the walls of the maze disappeared, leaving the participant in a desert environment. The participant was instructed to turn to face the location of the target object in the maze, named over the headphones, and to click the radio mouse once they thought they were facing the target. The participant was then instructed to walk forward until they thought they had reached the location of the target object, at which point the participant clicked the radio mouse again to end the trial. The experimenters then wheeled the participant through the desert environment to the starting location of the next trial, taking a circuitous route to prevent participants from learning more about object locations between trials. Position and orientation were recorded throughout the trial, with the locations of the two mouse clicks serving as endpoints for the shortcut.

Occasionally, participants would walk outside the bounds of the tracking area of the laboratory. In those cases, participants might not be able to walk as far as they wished, since they would have walked into a physical wall to do so. In such cases, the trial ended when the participant left the tracking area, and only initial angular data were included in analysis, and not the data regarding walking distance or final position.

Multiple dependent measures were taken for each trial, and analyses of all measures were included for completeness. (1) Angular measures included the difference between the correct heading and the actual heading of the participant when the participant left the first object, both signed and absolute unsigned errors. (2) Path length and path

length error measured the linear distance from the starting point to the stopping point of the shortcut taken by the participant, and how far that path length was off from the correct length. (3) Position error was the straight-line distance between the correct location and the participant's actual location at the end of the trial. (4) Out of bounds measured the number of trials in which the participant walked out of the bounds of the virtual world. (5) Response times for turning to face the target object and time to walk to the target were measured. Turn time was the time from when the participant walked into the starting object to when they clicked the mouse to indicate that they were facing the target object (first mouse click). Walk time was the time from the first mouse click to when they clicked the mouse to indicate they were at the target object (second mouse click). (6) Participants drew sketch maps of the maze after the test phase. These sketch maps were scored on a 1-10 scale by a rater that was not familiar with the hypotheses or the experimental conditions. Correlation analysis was also performed on several individual differences measures and performance in the shortcut task.

For all of the test conditions, 8 trial types were used, with each trial type consisting of one pair of objects (Figure 2). There were 5 trials per trial type, for a total of 40 trials. All trials were presented in a random order with the exception that trial types did not repeat back-to-back. Although the experimental groups received differing levels of information during the learning phase of the experiment, they all performed the test phase with full visual, vestibular, proprioceptive, and motor information. All groups must be tested under the same conditions to assess the effect of the learning. For example, a person exploring the environment in the Wheelchair conditions without

motor/proprioception might learn some of the general directions between objects, but might not learn the distances, so both need to be assessed during the test phase.

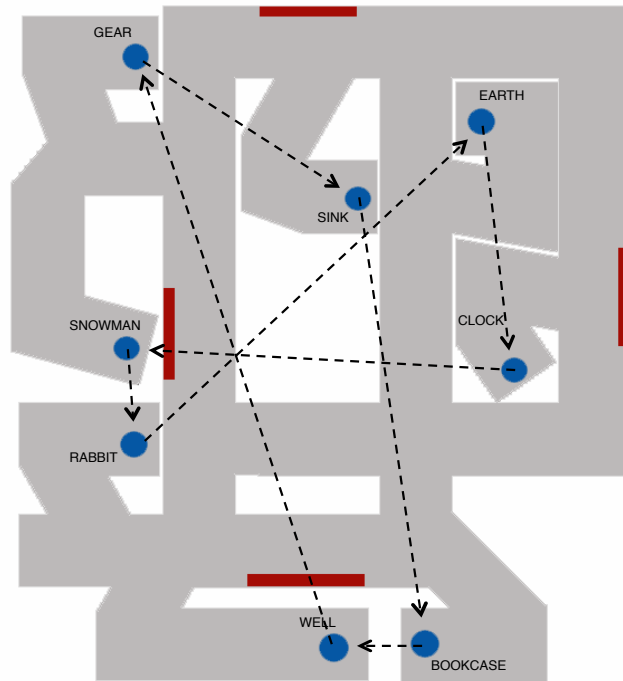


Figure 2. View of the eight test trial types used in Experiment 1. The maze itself was not present during the test phase.

Procedure

Participants read and signed a form indicating their informed consent to participate in the experiment. In the learning phase, participants were informed that they would be going through virtual hallways, like a hedge maze, and the task was to find all of the objects and learn their locations. They were informed that they would explore for 10 minutes. Participants were given several minutes in a practice environment, with objects not used during the experiment, to get used to being in virtual reality, and to give them practice if they were using the tablet PC (Free Wheelchair) or the keyboard (Free Video) as required by the condition. The practice was conducted in the same manner as the learning phase, so, for example, participants in the Guided Wheelchair group sat in

the wheelchair and were pushed during the practice. Eye height and total height was measured for those participants in the Video conditions. Participants in those conditions sat in a high chair at approximately their standing height, and their virtual eye height was set to their standing eye height.

After the practice, participants were guided to a start location, and the experimental maze was loaded. Participants explored for 10 minutes. In the test phase, the task instructions were given to the participants over the headphones. The experimenter then repeated the instructions, clarifying any questions the participant might have. The participants then completed two practice trials, using target pairs not encountered during the test phase. After the practice, participants completed 40 test trials, with frequent opportunity for breaks.

Following the test phase, all participants performed several additional tasks (see Appendix 1). First, they were asked to draw a map of the maze using a pen and paper. The names of the objects and paintings were provided. Participants were then asked about the strategies they used during the both the exploration and the test phase of the experiment. They filled out the Santa Barbara Sense of Direction Scale (SBSOD; Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) and a questionnaire regarding their experience playing video games. Finally, two standard spatial abilities assessment were taken: the Road Map Test modified with a 20-second timer (Money & Alexander, 1966; Zacks, Mires, Tversky, & Hazeltine, 2000), and the Perspective-Taking Test (PTSOT; Kozhevnikov & Hegarty, 2001). These tests both require participants to imagine a mental transformation of their own viewpoint while not turning either the paper or their head. In the Road Map Test, this mental transformation occurs while

following a route on a map of a city, and in the Perspective-Taking Test, this transformation takes place among a layout of objects.

Analysis

Analysis was performed using MatLab (MathWorks) and SPSS (IBM) software. Most comparisons were made with a 3x2x2 (information x decisions x sex) unequal-n ANOVA. Analysis of signed error of angular measures requires circular statistics, which were analyzed using a multiple-sample Watson-Williams one-way test for circular data (Batschelet, 1981). Currently there are no higher-order ANOVAs available for circular data, and so only one-way ANOVAs can be tested on circular data. Because different object pair trial types required different magnitudes of distances and angles, each trial type was analyzed separately. Additional analysis combined trial types by taking the mean of the unsigned angular errors (i.e. absolute errors). The remainder of the analyses examined both main effects and differences between trial types using trial type as a within-subjects factor.

Results

Angular Error

Initial angular error was measured in a number of ways. First, the accuracy of angular orientation was determined using the mean of the errors. Second, the precision of angular orientation was determined using the within-subject standard deviation of the orientation estimates.

Angular measures are circular variables, which tend to limit statistical analysis. In addition, the shortcut test had eight different trial types, and each trial type required a

different magnitude of turn to make a correct response. Thus, combining signed errors from those trial types might confound assessments of error. To respond to these concerns, two additional approaches were taken. First, the unsigned absolute errors (AE) were used. For each trial, the absolute value of the initial angular error was taken, and then the mean and standard deviation was taken over the 40 trials to provide measures of accuracy and precision. This step both removes the circularity of the data—allowing for more sophisticated statistical techniques—and combines all of the trial types into one measure. The second approach examined signed errors for each trial type separately. Signed errors indicate whether the participant overturned or underturned in making their response, with positive values indicating an overturn and negative signed error indicating an underturn. Mean constant error (CE) and variable error (VE) for the five trials of each of the eight trial types were assessed for each participant. The CE of each trial type was analyzed using Watson-Williams one-way ANOVAs in circular statistics. The VE for each trial type were analyzed using a repeated-measures ANOVA, with trial type as a within-subject item and information, decision-making, and sex as between-subjects factors.

Preliminary analysis. Preliminary analysis was performed using 16 participants per group, for a total of 96 participants. Mean absolute errors (AE) were analyzed using a 3x2x2 (information x decisions x sex) ANOVA. Means for the six groups were: Free Walking (mean = 68.801, SD = 27.392); Guided Walking (mean = 67.965, SD = 23.428); Free Wheelchair (mean = 74.878, SD = 17.814); Guided Wheelchair (mean = 75.144, SD = 14.813); Free Video (mean = 76.567, SD = 20.763); Guided Video (mean = 78.005, SD = 20.702). There was a significant main effect of sex ($F_{1,94} = 15.524, p < 0.001, \eta_p^2 =$

0.156). The effect of information was not significant ($F_{2,93} = 1.754$, $p = 0.179$, $\eta_p^2 = 0.040$), but a Helmert contrast showed a marginal difference between the Walking condition and the mean of the Wheelchair and Video conditions ($p = 0.073$). There was no effect of decision-making ($F_{1,94} = 0.005$, $p = 0.943$, $\eta_p^2 = 0.000$) and no interactions. Chance for AE is 90° , because if a participant is truly disoriented, their responses will be evenly distributed over $\pm 180^\circ$. The absolute value of that distribution is 180° , with a mean of 90° .

Variable error (VE) of the absolute angular errors were: Free Walking (mean = 48.638, SD = 14.668); Guided Walking (mean = 45.965, SD = 9.065); Free Wheelchair (mean = 51.608, SD = 5.582); Guided Wheelchair (mean = 53.124, SD = 5.921); Free Video (mean = 50.189, SD = 7.379), Guided Video (mean = 51.198, SD = 6.233).

Examination of the VE of the absolute angular errors revealed a main effect of sex ($F_{1,94} = 5.504$, $p = 0.021$, $\eta_p^2 = 0.061$), and a marginal main effect of information ($F_{2,93} = 3.010$, $p = 0.055$, $\eta_p^2 = 0.067$). A Helmert contrast showed that the Walking groups had significantly lower VE than the mean of the Wheelchair and Video groups ($p = 0.023$), and post-hoc Tukey tests showed that the Walking groups were significantly lower than the Video groups ($p = 0.047$). There was no effect of decision-making ($F_{1,94} = 0.001$, $p = 0.997$, $\eta_p^2 = 0.000$) and no interactions.

Because this preliminary analysis suggested that the primary effect of the experimental manipulations was that of information, rather than decision-making, this contrast was examined further by adding eight additional participants to the Free Walking and Free Video groups. The remainder of the analyses were conducted using unequal-n ANOVAs, with 24 participants in the Free Walking and Free Video conditions, and 16

participants in the Guided Walking, Free Wheelchair, Guided Wheelchair, and Guided Video conditions, for a total of 112 participants.

Final analysis. Figure 3 shows the mean angular AE with 112 participants. They were analyzed using a 3x2x2 (information x decisions x sex) unequal-n ANOVA. There was a significant main effect of sex ($F_{1,110} = 12.033$, $p = 0.001$, $\eta_p^2 = 0.107$), with men having lower angular errors than women. There was also a marginal main effect of information ($F_{2,109} = 2.708$, $p = 0.072$, $\eta_p^2 = 0.051$). There was no effect of decision-making ($F_{1,110} = 0.580$, $p = 0.448$, $\eta_p^2 = 0.006$), and no interactions. A Helmert contrast showed that the Walking groups had marginally lower absolute errors than the mean of the Wheelchair and Video groups ($p = 0.055$), and post-hoc Tukey tests showed that the Walking groups were significantly better than the Video groups ($p = 0.046$).

The within-subject VE of the AE were also analyzed with a 3x2x2 (information x decisions x sex) unequal-n ANOVA, and the results are shown in Figure 4. The results revealed a main effect of sex ($F_{1,110} = 5.654$, $p = 0.019$, $\eta_p^2 = 0.054$), with men being more consistent than women. There was also a main effect of information ($F_{2,109} = 3.189$, $p = 0.045$, $\eta_p^2 = 0.060$). A Helmert contrast found that the Walking groups were significantly less variable than the mean on the Wheelchair and Video groups ($p = 0.016$), while post-hoc Tukey tests found that the Walking groups were marginally more precise than the Wheelchair groups ($p = 0.060$). There was no effect of decision-making ($F_{1,110} = 0.030$, $p = 0.862$, $\eta_p^2 = 0.000$), and only a marginal information x decision-making x sex interaction ($F_{2,100} = 2.559$, $p = 0.082$, $\eta_p^2 = 0.049$).

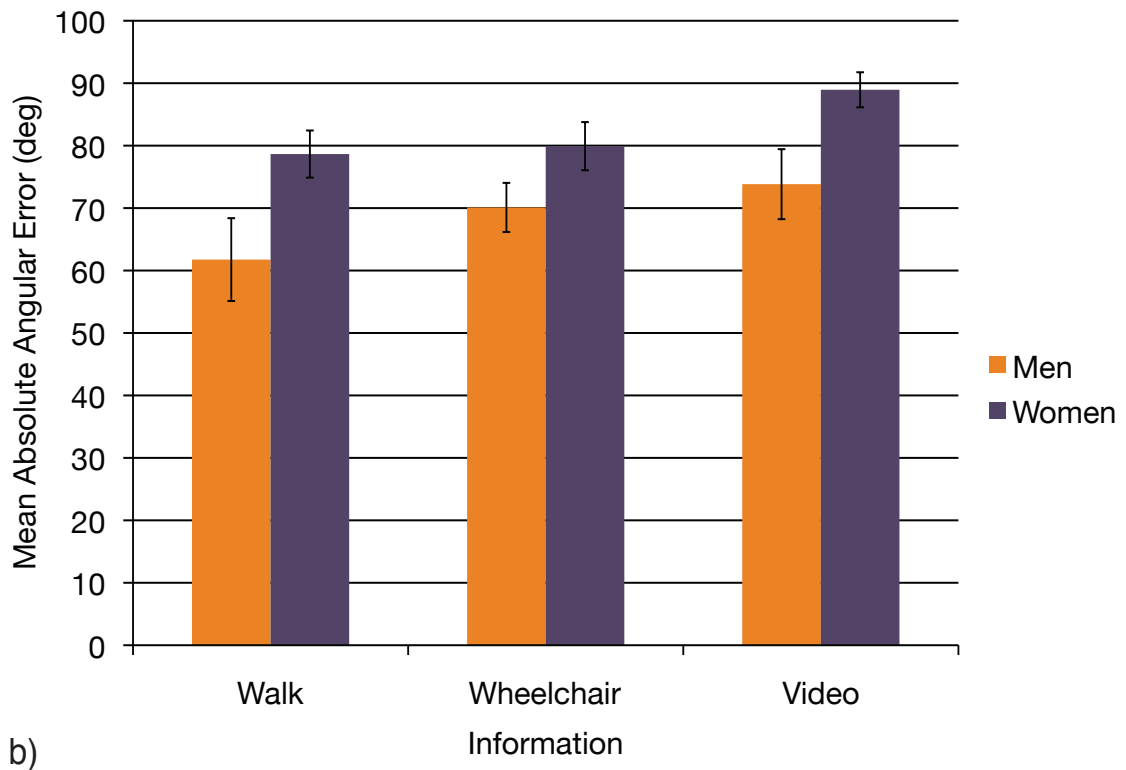
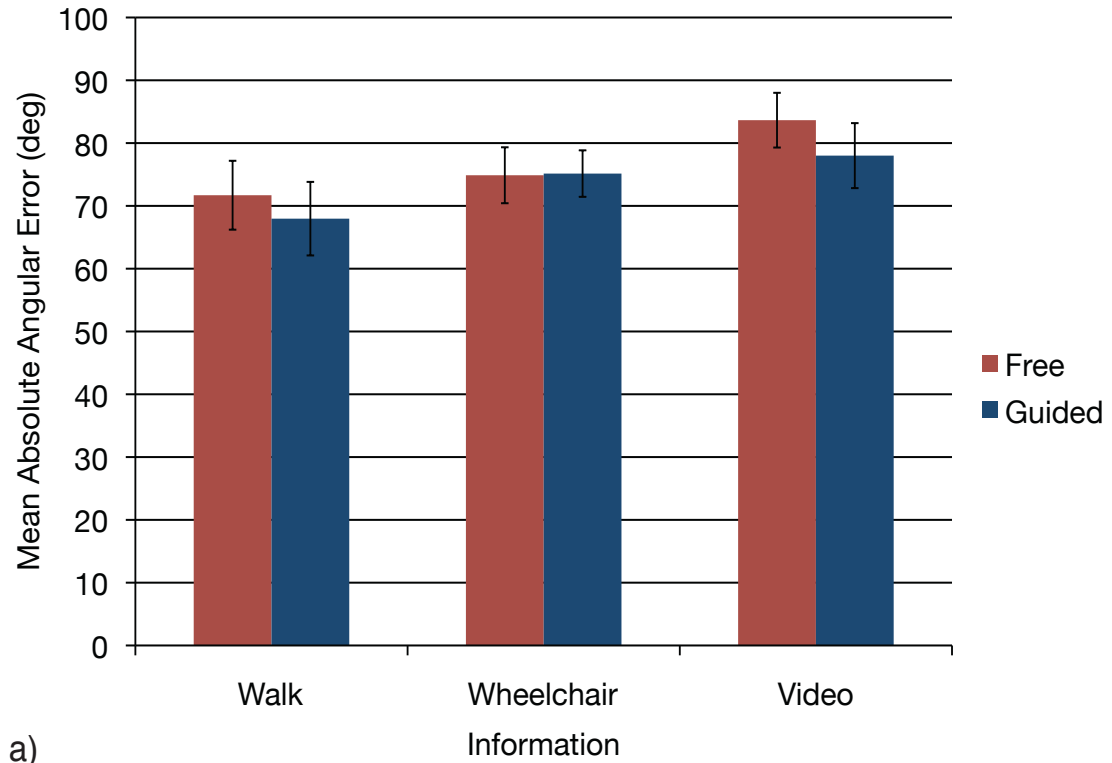


Figure 3. a) Mean absolute angular error, combining men and women into the six conditions. b) Mean absolute angular error, combining over the factor of decision-making. For both a) and b), chance is 90 degrees and $N = 112$.

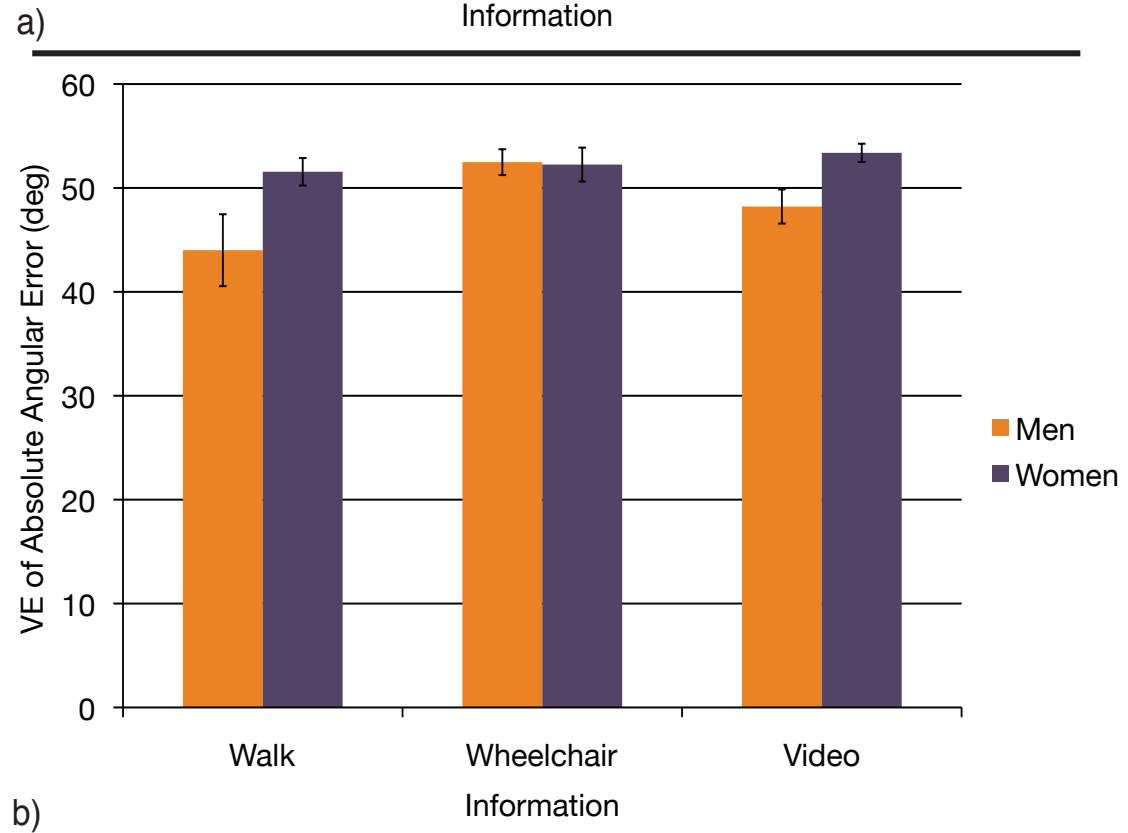
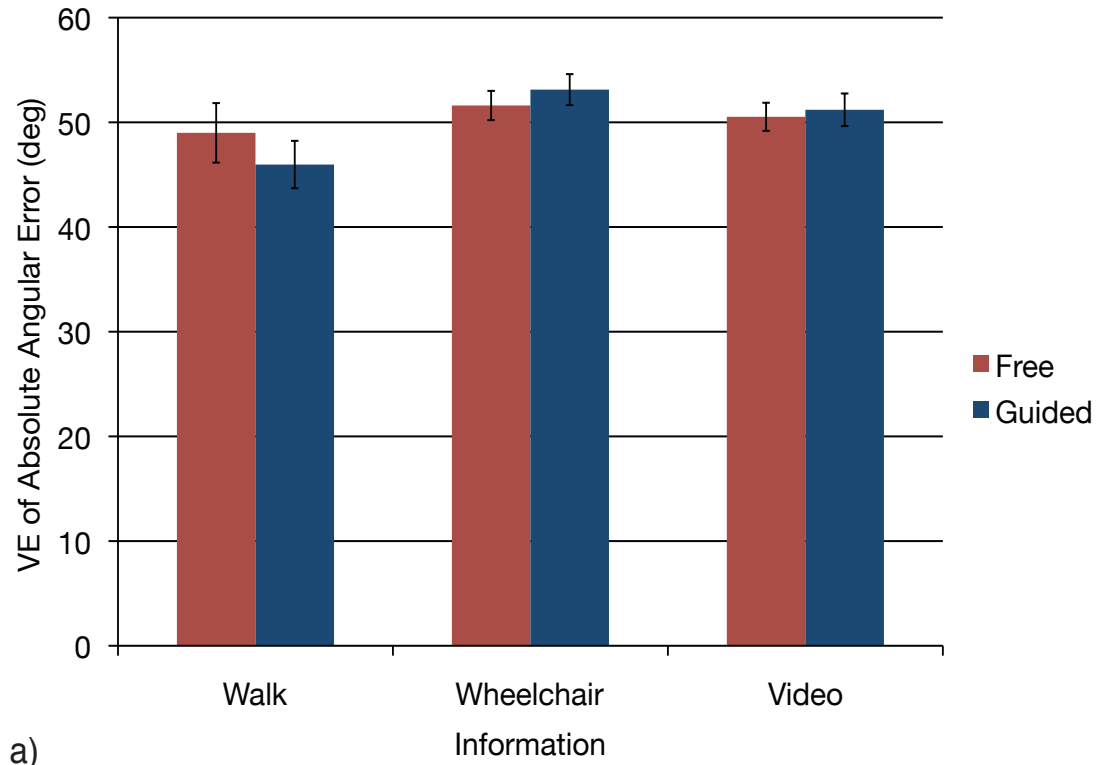


Figure 4. a) The within-subject VE of the absolute angular error, combining men and women into the six conditions. b) The within-subject VE of absolute angular error, combining over the factor of decision-making. N = 112.

Figure 5 shows the pattern of individual angular AE for the large Free Walking and Free Video groups (each N=24). Participants are listed in rank order, such that the worst performers are to the left and best performers are on the right. Examination of this figure suggests that the primary difference in mean AE is due to participants at the top end of the spectrum. Approximately half of the participants in each group are at or below chance levels in the shortcut task (absolute errors of 90 degrees). The upper third of the Free Walking group, however, appears to have learned quite a bit more of the environment than the top third of the Free Video group. In contrast, the results for VE between the Free Walking and Free Video group show that they are fairly similar throughout the distribution. Only those who had very low VE (who also tended to be those with low mean angular AE) showed differences between groups.

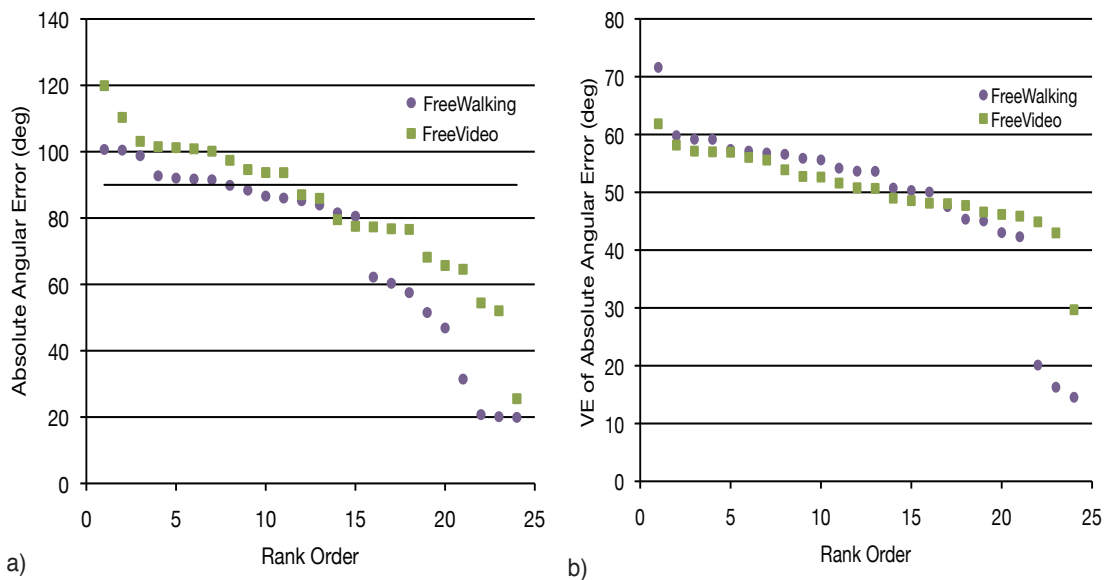


Figure 5. Individual performance in the Free Walking and Free Video conditions. a) Rank order of mean absolute angular errors. Chance is 90 degrees. b) Rank order of the standard deviation of the absolute angular errors.

Individual trial types were examined next. In order to examine the main effects of the conditions, one set of 8 Watson-Williams tests were conducted on the constant error (CE) for the information factor, and another set of 8 Watson-Williams tests were

conducted on the decision-making factor. The tests were Bonferroni-corrected for the two comparisons made on the data. The results are shown in Figures 6 and 7 and Table 2. One-way Watson-Williams tests for the decision factor found no significant differences between the Free and Guided conditions. Of the eight Watson-Williams tests for the factor of information, four had significant differences between the levels of information, with two more having marginal differences between the groups (Figure 7 and Table 2). In seven out of 8 trial types (including those that were not significant), the Walking group had mean signed errors closest to 0, and in the one condition they did not have the lowest error, the error in the Walking group was still fairly low, at -18.36 degrees.

Examination of the within-subject angular deviation was conducted with an item analysis, with trial type as a within-subject item, and information, decision-making, and sex as between-subjects factors. There was a significant effect of trial type ($F_{7,105} = 16.646$, $p < 0.001$, $\eta_p^2 = 0.143$). Neither the interactions with trial type nor the main effects were significant.

Information			Decision-making	
F	p-value		F	p-value
4.906	0.013*		0.434	0.513
0.861	0.431		1.695	0.198
4.878	0.013*		0.040	0.842
1.605	0.215		0.050	0.823
4.583	0.017*		0.091	0.765
8.214	0.001**		0.010	0.921
2.832	0.072		0.227	0.636
2.892	0.0686		1.672	0.201

Table 2. Results of signed angular error. Left: Overall Watson-Williams test comparing all six groups. Middle: Watson-Williams tests comparing the three levels of information (combining Free and Guided). Right: Watson-Williams tests comparing two levels of decision-making (combining Walk, Wheelchair, and Video).

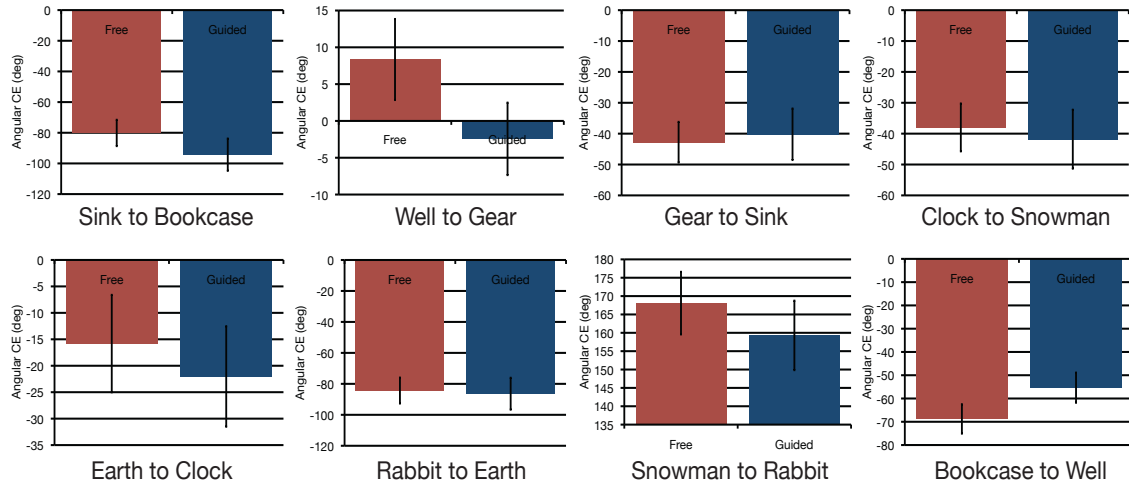


Figure 6. Angular CE for the eight trial types. Each graph depicts the combined groups of the Free and Guided conditions, illustrating the main effect of decision-making. None of the comparisons were significantly different.

Path Length Error

Because different trial types require different path length responses, path length was examined by analyzing trial types using the path length and path length error for each trial type for each participant, using a repeated-measures ANOVA as a within-subject measure. Path length error only includes trials in which the participant stayed within the bounds of the tracking space.

Item analysis of the trial types for path length error was conducted using a repeated-measures design for trial type. This analysis found a main effect of trial type ($F_{7,105} = 477.209$, $p < 0.001$, $\eta_p^2 = 0.827$) and a trial type x sex interaction ($F_{7,105} = 4.504$, $p < 0.001$, $\eta_p^2 = 0.043$).

Participants tended to overshoot short distances and undershoot long distances. There was also a significant between-subjects main effect of information ($F_{2,109} = 3.571$, $p = 0.032$, $\eta_p^2 = 0.067$) and a significant effect of sex ($F_{1,110} = 7.522$, $p = 0.007$, $\eta_p^2 = 0.070$). Men tended to walk further than women. A Helmert contrast of the information showed that the Walking groups walked further than the mean of the Wheelchair and

Video groups ($p = 0.020$), with post-hoc Tukey tests showing that the Walking groups were significantly longer than the Video groups ($p = 0.020$).

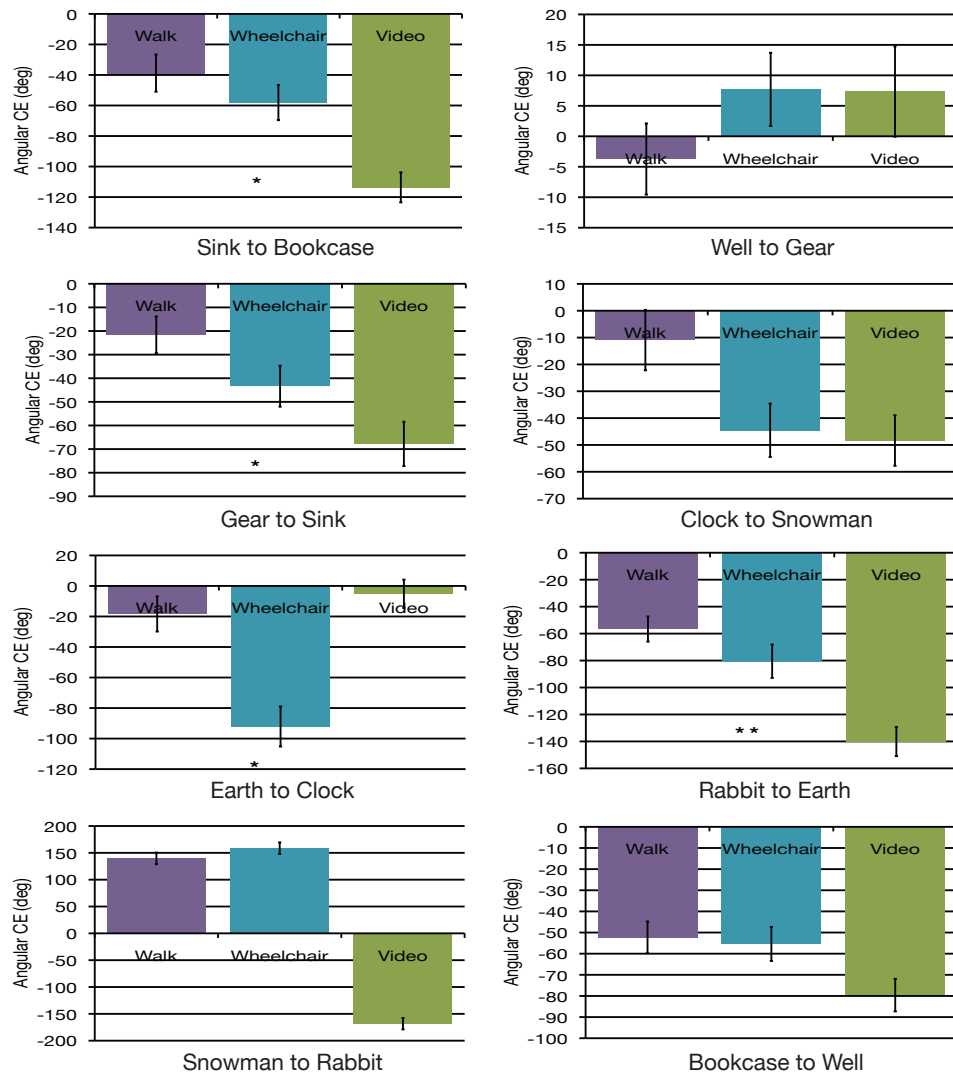


Figure 7. Angular CE for the eight trial types. Each graph depicts the combined groups of the Walk, Wheelchair, and Video groups, illustrating the main effect of information. Significant main effects are starred.

Additional item analysis was performed on individual trial types of the path length itself, as measured by the straight-line distance between the location the participant first clicked the mouse to the location where the trial ended (Figures 8 and 9). This analysis showed a significant effect of trial type ($F_{7,105} = 20.509$, $p < 0.001$, $\eta_p^2 = 0.170$) and a significant trial type x sex interaction ($F_{7,105} = 4.361$, $p < 0.001$, $\eta_p^2 =$

0.042). The object pairs for each trial type were located at different distances, so the significant effect of trial type suggests that participants were distinguishing between trial types. Between-subjects effects found a main effect of information ($F_{2,109} = 3.393$, $p = 0.038$, $\eta_p^2 = 0.064$), a main effect of sex ($F_{1,110} = 7.750$, $p = 0.006$, $\eta_p^2 = 0.072$), and a marginal information x decisions x sex interaction ($F_{2,100} = 3.096$, $p = 0.050$, $\eta_p^2 = 0.058$). Men tended to walk further than women. A Helmert contrast revealed that the Walking groups were significantly longer than the mean of the Wheelchair and Video groups ($p = 0.024$), and post-hoc Tukey tests found that the Walking groups also walked significantly farther than the Video groups ($p = 0.024$).

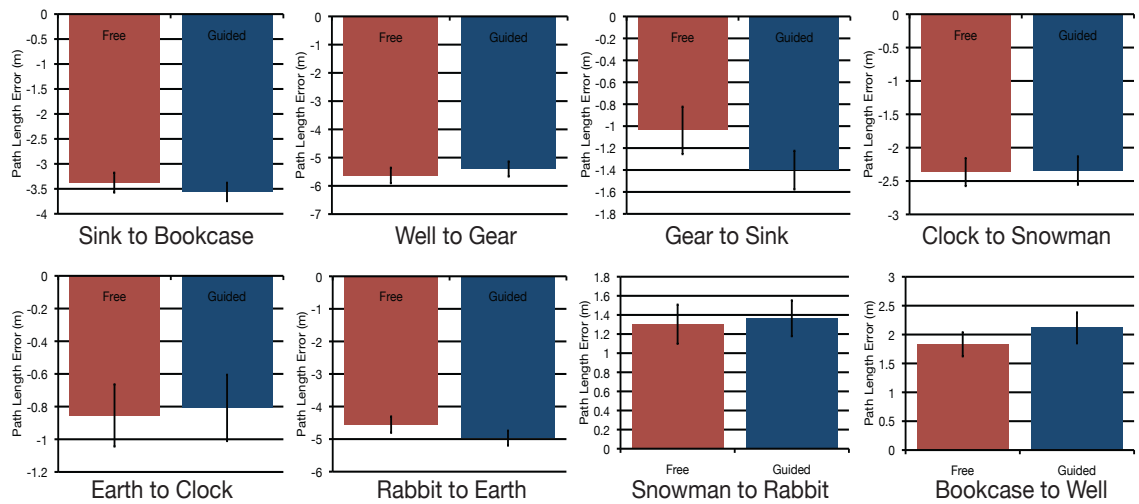


Figure 8. Signed path length errors for the eight trial types. Each graph depicts the combined groups of the Free and Guided conditions, illustrating the main effect of decision-making. None of the comparisons were significantly different.

Position Error

Position error was computed as the positive distance between the final location of the participant on a trial and the actual location of the target object. Position error was measured for each trial and averaged across all forty trials. Position error was also examined for each of the eight trial types. Both mean position error and the VE of

position error were analyzed. Mean position errors were: Free Walking (mean = 5.552, SD = 1.664); Guided Walking (mean = 5.614, SD = 1.422); Free Wheelchair (mean = 5.922, SD = 1.006); Guided Wheelchair (mean = 5.826, SD = 0.749); Free Video (mean = 6.177, SD = 1.048); Guided Wheelchair (mean = 5.901, SD = 0.962). Within-subject standard deviations for position error were: Free Walking (mean = 2.740, SD = 0.528); Guided Walking (mean = 2.913, SD = 0.294); Free Wheelchair (mean = 2.899, SD = 0.432); Guided Wheelchair (mean = 2.957, SD = 0.245); Free Video (mean = 3.080, SD = 0.299); Guided Wheelchair (mean = 3.122, 0.401).

A 3x2x2 (information x decisions x sex) unequal-n ANOVA on the mean position error found only a main effect of sex ($F_{1,110} = 6.848$, $p = 0.010$, $\eta_p^2 = 0.064$), with women having larger position errors than men. There were no effects of information ($F_{2,109} = 1.413$, $p = 0.248$, $\eta_p^2 = 0.027$) or decision-making ($F_{1,110} = 0.290$, $p = 0.655$, $\eta_p^2 = 0.002$). Examination of the VE of position error found a main effect of information ($F_{2,109} = 5.126$, $p = 0.008$, $\eta_p^2 = 0.093$). There was no effect of decision-making ($F = 1.561$, $p = 0.214$, $\eta_p^2 = 0.214$). A Helmert contrast showed that the Walking groups were significantly less variable than the mean of the Wheelchair and Video groups ($p = 0.015$), and post-hoc Tukey tests showed that the Walking groups were significantly less variable than the Video groups ($p = 0.003$), but not the Wheelchair groups ($p = 0.387$).

Examination of each trial type was conducted using a repeated-measures ANOVA. Item analysis of position error means found an effect of trial type ($F_{7,105} = 120.431$, $p < 0.001$, $\eta_p^2 = 0.546$), a significant trial type x information interaction ($F_{14,98} = 2.586$, $p = 0.001$, $\eta_p^2 = 0.049$), a trial type x sex interaction ($F_{7,105} = 4.733$, $p < 0.001$, $\eta_p^2 = 0.045$), a trial type x information x decision-making interaction ($F_{14,98} = 1.746$, $p =$

0.043, $\eta_p^2 = 0.034$), and a trial type x decision-making x sex interaction ($F_{7,105} = 2.277$, $p = 0.027$, $\eta_p^2 = 0.022$). Between-subjects effects were not significant.

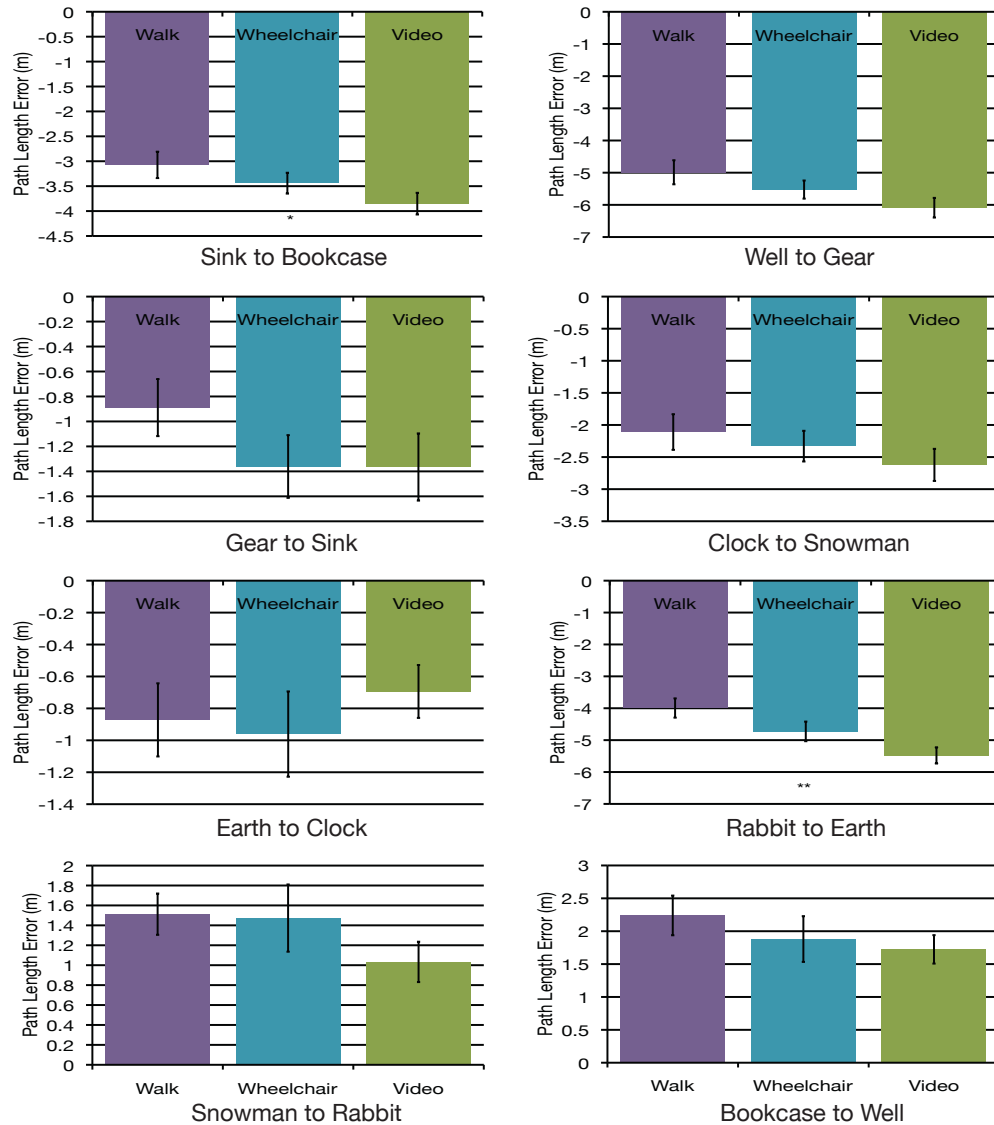


Figure 9. Signed path length error for the eight trial types. Each graph depicts the combined groups of the Walk, Wheelchair, and Video groups, illustrating the main effect of information. Significant main effects are starred.

For the standard deviation of position error, broken down by trial type, there was a main effect of trial type ($F_{7,105} = 26.642$, $p < 0.001$, $\eta_p^2 = 0.210$) and a significant trials x decision-making x sex interaction ($F_{7,105} = 2.689$, $p = 0.009$, $\eta_p^2 = 0.026$). Between-subject effects were not significant.

Out of Bounds

When participants leave the tracking area of the room, it may indicate that they were disoriented. Participants may not know where the target object is located relative to their starting location, or how the maze is generally structured. However, examination of the number of times participants went out of the bounds of the tracking area showed no effect of condition. Item analysis showed a significant effect of trial type ($F_{7,105} = 12.742$, $p < 0.001$, $\eta_p^2 = 0.113$) and a significant trial type x sex interaction ($F_{7,105} = 3.923$, $p < 0.001$, $\eta_p^2 = 0.038$). There were no other effects.

Response Time

Response time analysis examined four variables: mean time to turn to face the target (mean turn time) and its VE, and mean time to walk to the target after turning (mean walk time) and its VE. These variables were tested both with all trial types combined and separately for each trial type.

A 3x2x2 unequal-n ANOVA for mean turn time found only a marginal information x decision-making x sex interaction ($F_{2,100} = 2.851$, $p = 0.062$, $\eta_p^2 = 0.054$). Deviation of turn time found a marginal main effect of sex ($F_{1,110} = 3.492$, $p = 0.065$, $\eta_p^2 = 0.034$), with men tending to be more variable and a marginal information x decision-making x sex interaction ($F_{2,100} = 2.785$, $p = 0.067$, $\eta_p^2 = 0.053$). A Helmert contrast showed a marginal effect of information ($p = 0.076$) when comparing the Walking groups to the combined Wheelchair and Video groups, with Walking tending to be more variable in turn times.

Examination of the different trial types for mean turn time was conducted with a repeated-measures ANOVA, with trial type as the within-subjects factor, and

information, decision-making, and sex as between-subject factors. This item analysis found a main effect of trial type ($F_{7,105} = 7.474$, $p < 0.001$, $\eta_p^2 = 0.070$) and a significant trial type x sex interactions ($F_{7,105} = 3.113$, $p = 0.003$, $\eta_p^2 = 0.030$). There were no significant effects of the VE of turn time.

An ANOVA on walking time found a marginal effect of sex ($F_{1,110} = 3.332$, $p = 0.071$, $\eta_p^2 = 0.032$), with men tending to take more time walking than women. There were no significant effects of the VE of walking time, although a Helmert contrast found a marginally significant difference between the Walking groups and the mean of the Wheelchair and Video groups ($p = 0.065$), with the Walking groups most variable.

An item analysis of walking time for each trial type was conducted the same way as for turn times. A main effect of trial type was observed ($F_{7,105} = 17.046$, $p < 0.001$, $\eta_p^2 = 0.146$), as was a significant trial type x sex interaction ($F_{7,105} = 4.024$, $p < 0.001$, $\eta_p^2 = 0.039$). A similar analysis of the VE of walking times found a main effect of trial type ($F_{7,105} = 3.302$, $p = 0.002$, $\eta_p^2 = 0.032$).

Map Drawing

The sketch maps that participants drew after the test phase were scored on a 1-10 scale by a rater that was not familiar with the hypotheses or the experimental conditions. Examples of sketch maps are shown in Figure 10. Sketch maps were rated for general accuracy of spatial layout, with the layout of the hallways and relative positioning of the objects and paintings given the most weighing. Results of map drawing analysis are shown in Figure 11. A 3x2x2 (information x decisions x sex) unequal-n ANOVA found

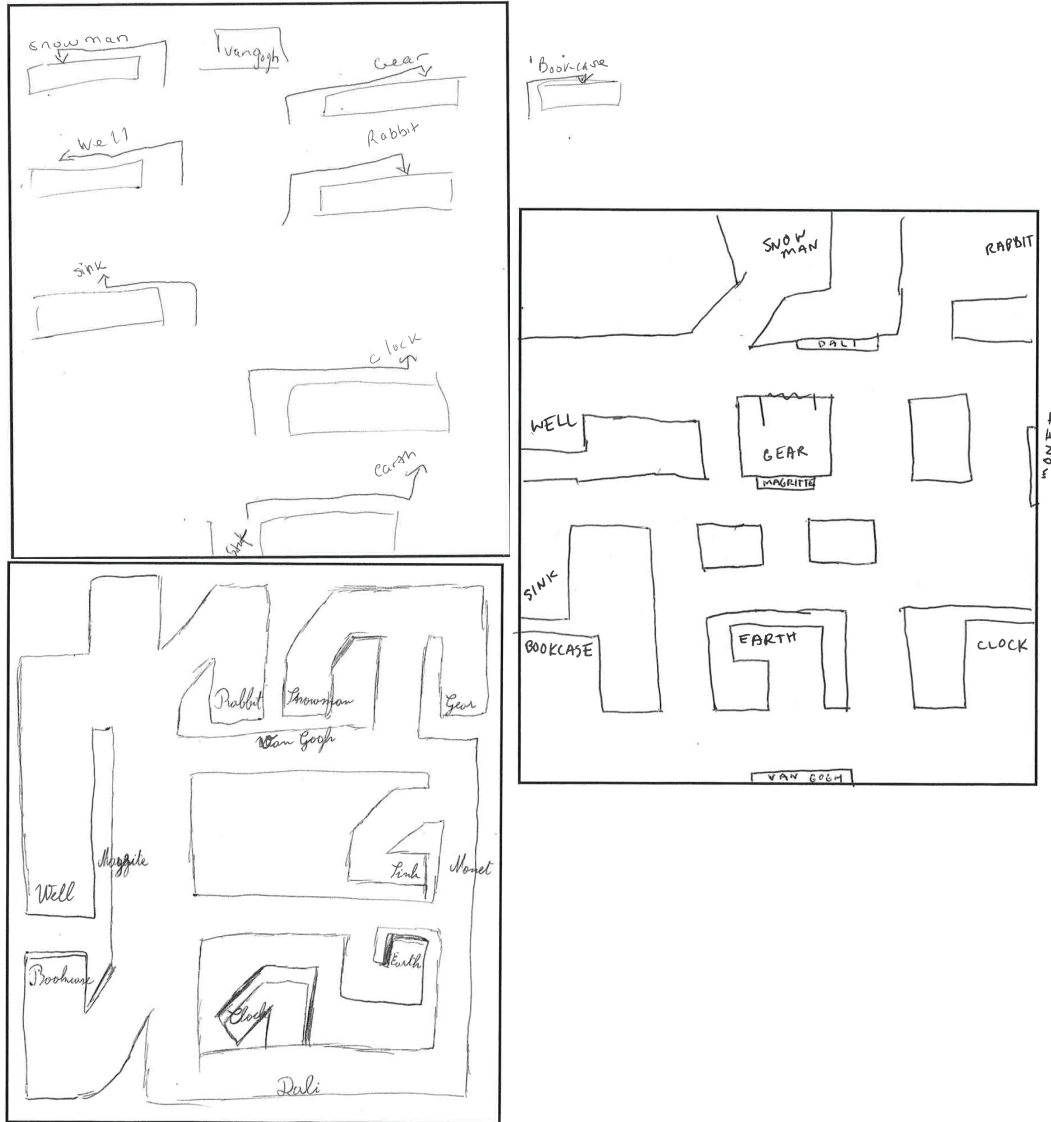


Figure 10. Examples of sketch maps drawn by participants in Experiment 1.

a main effect of sex ($F_{1,110} = 16.906$, $p < 0.001$, $\eta_p^2 = 0.145$), a main effect of decision-making ($F_{1,110} = 5.630$, $p = 0.020$, $\eta_p^2 = 0.053$), and an information x decision-making interaction ($F_{2,106} = 8.051$, $p = 0.001$, $\eta_p^2 = 0.139$). There was also a marginal

information x decision-making x sex interaction ($F_{2,100} = 2.419$, $p = 0.0994$, $\eta_p^2 = 0.046$). Men drew better sketch maps than women, and those in the guided conditions drew better sketch maps than those who were free to make decisions about exploration. Those in the

Guided Video condition also tended to draw maps that were almost as good as those in the Free Walking group, while the Free Video group drew less accurate maps.

Individual Differences

The large individual differences highlighted in Figure 5 warrant further consideration. First, it must be established that the experimental groups did not differ on measures of individual differences that might affect the outcome of the experimental manipulations. Second, it is of interest to determine what individual factors correlate with performance on this shortcut task.

There are a number of potential measures of individual differences that could be considered. First, there are measures that are related to the participant's spatial abilities or experiences. These measures included age, score on the SBSOD Scale (note that a lower score indicates a better self-reported sense of direction), score on the PTSOT (lower scores mean lower error and thus better spatial ability), score on the Road Map Test (higher scores indicate higher spatial ability), current video game usage (question 4 on the questionnaire, scores inverted so higher rating indicates more video game usage), current use of 1st person navigational video games (question 6), and past use of 1st person navigational video games (question 8).

The other measures are related to the participant's experience during the testing session itself. These measures included nausea ratings, rating of immersion in the virtual world, distance traveled during the learning phase, total angular rotation during the learning phase, mean number of times visiting each object during exploration, standard deviation of the object visits during the learning phase, and range of the number of object visits during the learning phase. The last two measures require greater explanation.

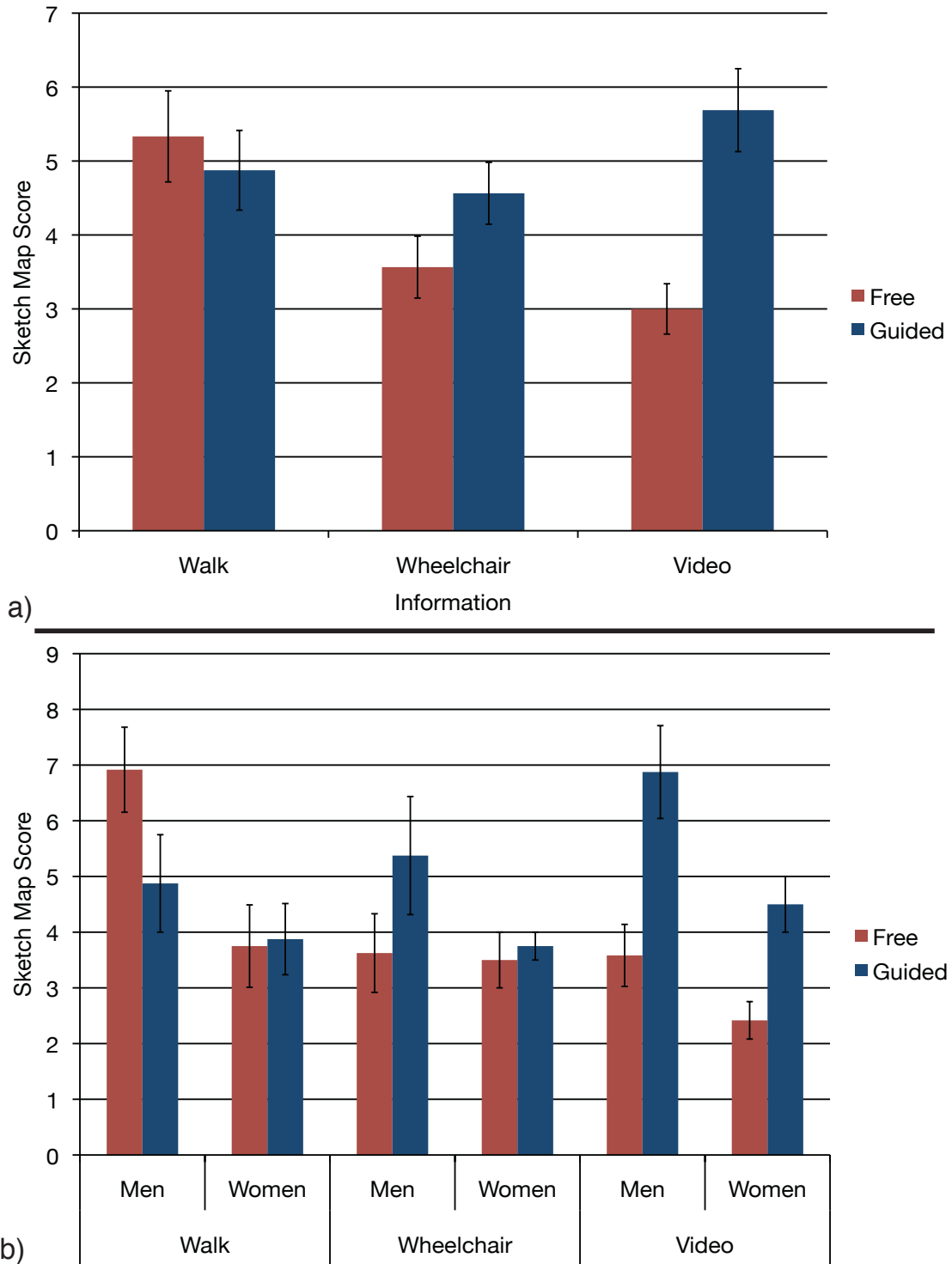


Figure 11. Scores from sketch maps that participants drew after the test phase of Experiment 1. Scores ranged from 1 to 10. a) Sketch map scores for the six experimental groups. b) Sketch map scores of the six experimental groups separated into men and women.

During the course of the 10-minute learning phase, participants visited each object at least once, and maybe up to 7 times. They visited some objects more than others, and so both the mean and the standard deviation of the visits to the 8 objects were calculated. The range measure means that if the participant visited the bookcase most often with 6 visits, for example, and the clock the least often, with 2 visits, then the range is 4. This measure is similar to the standard deviation, since they both tend to measure how evenly a participant explored the environment. All of these measures of the participant's experience in the experiment could be related to their individual spatial abilities, since those with high abilities might visit more objects on average, or turn their heads more when exploring, or explore more evenly, and could be related to their performance in the test phase. Those in the guided explore conditions should be very close to the Free Walking group on many of the measures related to exploration experience (since they were matched to go on the same paths), but may respond to those factors in a different way.

Group differences. The first analysis of individual differences was aimed at determining whether the experimental groups were equivalent on these measures. This step insures that the random assignment of participants did not somehow lead to one group having higher spatial abilities than the others. 3-way ANOVAs (information x decisions x sex) were performed on the 7 measures of spatial abilities and experience.

For age, there was a significant information x sex interaction ($F_{2,106} = 4.579$, $p = 0.013$, $\eta_p^2 = 0.084$). Post-hoc Tukey tests showed a marginal difference in age between the Wheelchair and Video groups ($p = 0.082$). Men in the Wheelchair groups tended to

be somewhat older than those in the Walk or Video conditions, although all group averages ranged fairly narrowly between 19-25.

Tests of spatial abilities primarily showed main effects of sex, with women tending to have lower spatial abilities than men. The SBSOD self-assessment only showed a sex difference ($F_{1,110} = 5.622$, $p = 0.020$, $\eta_p^2 = 0.053$). The PTSOT perspective-taking test also showed a sex difference ($F_{1,110} = 10.085$, $p = 0.002$, $\eta_p^2 = 0.092$) and a significant information x sex interaction ($F_{2,106} = 3.376$, $p = 0.038$, $\eta_p^2 = 0.063$). Women in the Wheelchair groups tended to have better PTSOT scores than women in the Walking or Video groups. The Road Map test also had a significant sex difference ($F_{1,110} = 10.080$, $p = 0.002$, $\eta_p^2 = 0.092$) and also a significant difference between the two decision-making groups ($F_{1,110} = 5.738$, $p = 0.018$, $\eta_p^2 = 0.055$). Those in the Guided conditions showed higher Road Map test scores than those who were free to make decisions.

There were also sex differences in video game use, with men using video games more often than women. Current video game use showed a significant sex difference ($F_{1,110} = 7.496$, $p = 0.007$, $\eta_p^2 = 0.070$), but also a significant difference between the levels of information ($F_{2,109} = 3.425$, $p = 0.036$, $\eta_p^2 = 0.065$) and a significant information x decision-making interaction ($F_{2,106} = 3.362$, $p = 0.039$, $\eta_p^2 = 0.064$). Post-hoc Tukey tests found that those in the Video groups played marginally more video games than those in the Walking groups ($p = 0.061$). Those in the Guided Video group played the most video games, while those in the Guided Walking group played the least. There were no differences between groups in current use of 1st person navigational video games, while past use of navigational video games revealed a significant sex difference

($F_{1,110} = 14.294$, $p < 0.001$, $\eta_p^2 = 0.125$) and a significant difference between levels of information ($F_{2,109} = 3.334$, $p = 0.040$, $\eta_p^2 = 0.063$). Post-hoc Tukey tests showed that the Video groups had played significantly more 1st person navigational video games in the past than those in the Walking groups ($p = 0.044$).

The group differences primarily reflected sex differences. These differences in spatial ability between men and women might account for the main effects of sex observed in the shortcut test. Higher spatial abilities may assist in learning survey information. Likewise, men tended to have more video game experience, which often involves learning the layout of a large and complex environment. Those in the Video conditions also tended to have more video game experience than those in the Walking conditions. Those in the Free Video condition who were not comfortable with video games might have failed to find all of the objects, leading to fewer participants in this group with low video game experience. If video game experience does assist in survey learning, then the additional experience in the Video groups would likely have made differences in performance in the experimental task smaller, but significant differences in information were still observed.

Differences in VR experience. Analysis of differences in VR experience provides a way of examining whether certain conditions were associated with different experiences. For example, it is possible that experiencing the virtual world through a video may lead to less feelings of immersion. 3-way ANOVAs (information x decisions x sex) were performed on the 7 measures of VR experience.

There were differences in nausea ratings between the different levels of information ($F_{2,109} = 7.526$, $p = 0.001$, $\eta_p^2 = 0.131$). Post-hoc Tukey tests showed that the

Walking groups experienced significantly less nausea than the Video groups ($p < 0.001$) and marginally less nausea than the Wheelchair groups ($p = 0.066$). Increased nausea ratings could mean that participants were distracted from learning the environment, possibly leading to worse performance in the Wheelchair and Video groups.

There were no differences between the groups in their ratings of immersion in the virtual environment.

For distance traveled during the learning phase, there was a significant information x sex interaction ($F_{2,106} = 3.993$, $p = 0.022$, $\eta_p^2 = 0.075$). Men in the Video conditions tended to travel the furthest during exploration, likely due to the Free Video condition. Total angular rotations revealed differences between levels of information ($F_{2,109} = 9.020$, $p < 0.001$, $\eta_p^2 = 0.155$), a sex difference ($F_{1,110} = 5.678$, $p = 0.019$, $\eta_p^2 = 0.055$), a significant information x decision-making interaction ($F_{2,106} = 7.128$, $p = 0.001$, $\eta_p^2 = 0.127$). Post-hoc Tukey tests showed the Wheelchair groups had significantly less head rotation than both the Walk ($p < 0.001$) and Video groups ($p = 0.002$). Women tended to have less angular rotation than men, especially in the Free Video condition.

Examination of the number of objects visited during exploration found significant differences in between the three levels of information ($F_{2,109} = 3.570$, $p = 0.032$, $\eta_p^2 = 0.067$) and an information x sex interaction ($F_{2,106} = 5.433$, $p = 0.006$, $\eta_p^2 = 0.098$). Post-hoc Tukey tests showed that the Wheelchair groups visited significantly fewer objects than both the Walk ($p = 0.049$) and the Video ($p = 0.047$) groups. Women tended to visit fewer objects in the Wheelchair and Video groups.

The two measures related to evenness of exploration also showed some group differences. For standard deviation of the number of objects visited during the learning

phase, there were significant differences in the three levels of information ($F_{2,109} = 4.274$, $p = 0.017$, $\eta_p^2 = 0.079$), significant differences between the two levels of decision-making ($F_{1,110} = 7.075$, $p = 0.009$, $\eta_p^2 = 0.066$), a significant information x decision-making interaction ($F_{2,106} = 5.893$, $p = 0.004$, $\eta_p^2 = 0.105$), and a significant information x sex interaction ($F_{2,106} = 4.194$, $p = 0.018$, $\eta_p^2 = 0.077$). Post-hoc Tukey tests showed that the Video conditions had significantly higher standard deviations than the Walk groups ($p = 0.001$) and marginally higher deviations than the Wheelchair groups ($p = 0.055$). Overall, those who made decisions had higher standard deviation than those who were guided. However, those in the Free Walking group had the lowest standard deviations of any group, suggesting that the main effect of decision-making was driven primarily by the Free Wheelchair and Free Video groups. The effects for the range of the number of objects visited during the learning phase followed a similar pattern.

Some of the factors in VR experience showed significant sex differences. If visiting more objects, traveling more distance, or having greater head rotations help with survey learning, these sex differences could account for the differences in performance. It is also possible that spatial abilities are related to these factors. The evenness of exploration factors did show differences between the levels of information, with Walking tending to be most even, and Video the least even. It is unclear whether the people in those conditions tended to explore unevenly because of some difference in spatial abilities, or whether having less information makes it more likely that a person will explore unevenly.

Correlations with performance. For the second aim of the individual differences analysis, two approaches were taken. The first approach combined

performance over all 112 participants from all groups. This approach provides large statistical power to detect small effects. However, combining over all groups ignores any effects of the experimental manipulations. The second approach examined primarily the Free Walking group, which may be considered the condition closest to a control, with full idiothetic information and full access to cognitive decisions about exploration.

Examination of several measures in the Free Walking group provides a closer look into the role of individual differences under close-to-normal exploration conditions. Because the dependent variable of absolute angular error proved to be the primary performance measure, with the other measures showing similar patterns, it was the focus of the correlation analysis. Both the means (accuracy) and within-subject standard deviations (precision, VE) of absolute angular error (angular AE) were tested.

	r	p-value	df
Age	-0.017	0.859	110
SBSOD	0.155	0.102	110
PTSOT	0.214	0.024*	110
Road Map Test	-0.281	0.003**	109
Current Video Game Use	-0.103	0.281	109
Current Navigational Games	-0.079	0.407	110
Past Navigational Games	-0.053	0.576	110
Nausea	0.141	0.137	110
Immersion	0.089	0.354	109
Distance Traveled during Exploration	-0.062	0.517	108
Total Angular Rotation during Exploration	-0.181	0.058	108
Mean Number of Objects Visited during Exploration	-0.054	0.572	110
StDev of Objects Visited during Exploration	0.188	0.047*	110
Range of Objects Visited during Exploration	0.191	0.043*	110

Table 3. Correlation coefficients for individual difference measures and angular AE in the shortcut test, combined over all 112 participants in Experiment 1.

Results of the overall correlations are listed in Tables 3 and 4 and Figure 12. The results of the correlations suggest that some of the measures of participants' spatial abilities, regardless of the experimental manipulation, do correlate with performance in

the shortcut task. Angular AE was correlated with scores on the PTSOT perspective-taking test ($r_{110} = 0.214$, $p = 0.024$) and the Road Map test ($r_{109} = -0.281$, $p = 0.003$), both indicating that better spatial abilities predicted better performance in the test. It also correlated with the two measures of evenness of exploration also correlated with accuracy (Standard deviation of object visits: $r_{110} = 0.188$, $p = 0.047$; Max-min object visits: $r_{110} = 0.191$, $p = 0.043$). Total angular rotation during exploration was marginally correlated ($r_{108} = -0.181$, $p = 0.058$), with those who rotated their heads more having fewer errors.

	r	p-value	df
Age	0.096	0.313	110
SBSOD	0.053	0.581	110
PTSOT	0.156	0.101	110
Road Map Test	-0.171	0.072	109
Current Video Game Use	-0.095	0.322	109
Current Navigational Games	-0.190	0.045*	110
Past Navigational Games	-0.059	0.533	110
Nausea	0.012	0.898	110
Immersion	0.125	0.193	109
Distance Traveled during Exploration	0.068	0.479	108
Total Angular Rotation during Exploration	-0.093	0.336	108
Mean Number of Objects Visited during Exploration	0.081	0.398	110
StDev of Objects Visited during Exploration	0.147	0.121	110
Range of Objects Visited during Exploration	0.188	0.047*	110

Table 4. Correlation coefficients for individual difference measures and VE of absolute angular error in the shortcut test, combined over all 112 participants in Experiment 1.

Variable error correlated with current use of navigational video games ($r_{110} = -0.190$, $p = 0.045$) and the range of object visits during the learning phase ($r_{110} = 0.188$, $p = 0.047$). There was also a marginal correlation with the Road Map test ($r_{109} = -0.171$, $p = 0.072$). Those who had more video game experience were less variable, as were those who had greater spatial abilities. Those who were less variable during the learning phase were also less variable during the test phase.

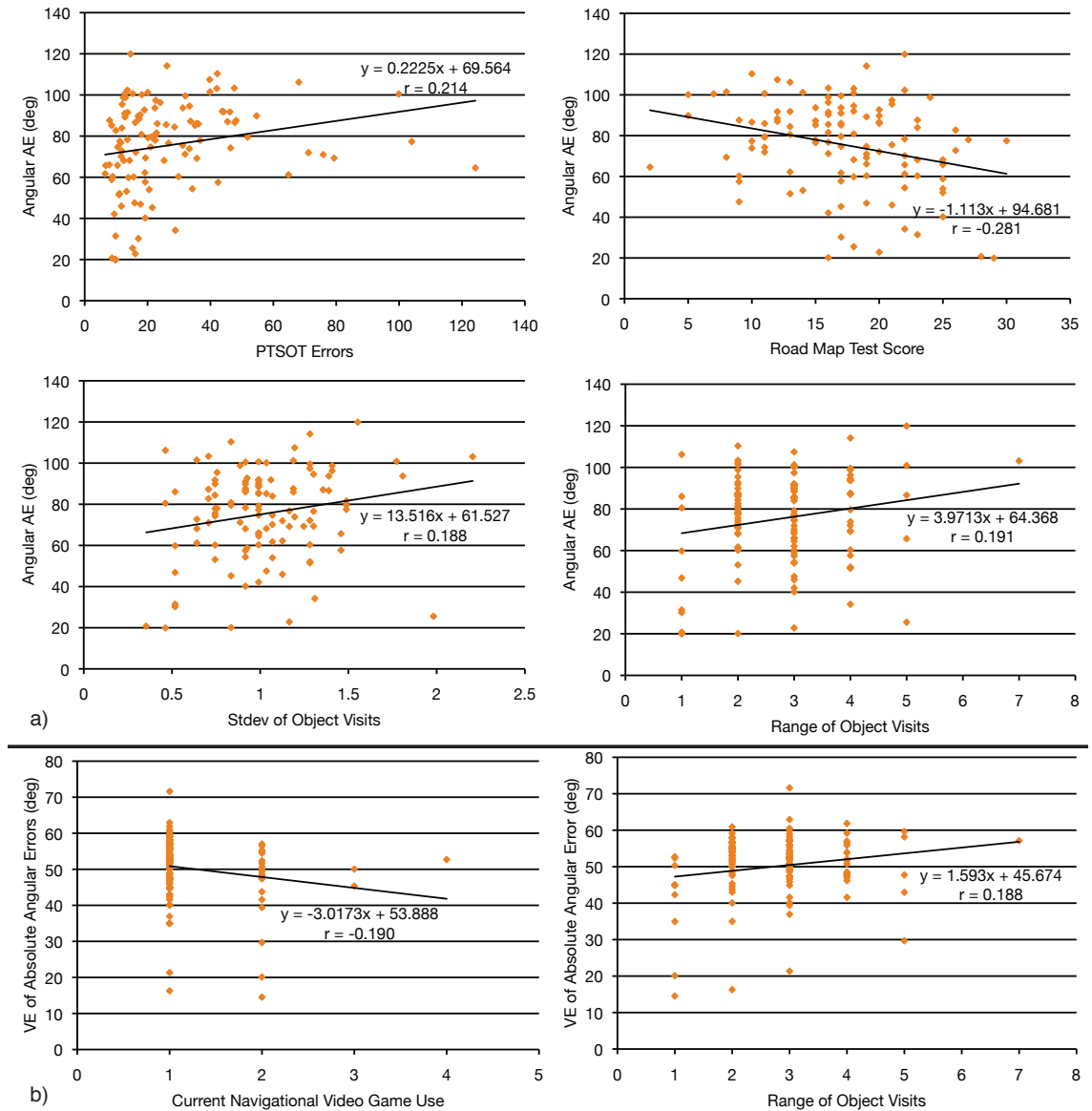


Figure 12. Correlations between performance in the shortcut test with individual difference measures for all participants. Each data point represents the mean score for one participant. a) Significant correlations of angular AE with PTSOT errors, Road Map Test scores, the standard deviation of the number of object visits during exploration, and the maximum-minimum number of object visits during exploration. b) Significant correlations of the VE of absolute angular errors with current use of navigational video games and the maximum-minimum number of object visits during exploration.

Examination of the figures shows that some of the correlations appear to be driven by the worst performers, while other correlations have more even distributions. For example, participants with particularly high errors on the PTSOT were unlikely to do well in the shortcut test, while those with low PTSOT errors had both high and low errors

in the shortcut test. In contrast, the Road Map Test appears to be fairly evenly distributed, with those with low Road Map Test scores performing poorly on the shortcut test and those with high Road Map Test scores performing well. Accordingly, the Road Map test also has the strongest correlation of any of the individual difference measures.

	r	p-value	df
Age	0.311	0.139	22
SBSOD	0.304	0.148	22
PTSOT	0.469	0.021*	22
Road Map Test	-0.547	0.006**	22
Current Video Game Use	-0.243	0.252	22
Current Navigational Games	-0.121	0.575	22
Past Navigational Games	0.068	0.144	22
Nausea	-0.162	0.752	22
Immersion	-0.056	0.800	22
Distance Traveled during Exploration	-0.196	0.359	22
Total Angular Rotation during Exploration	-0.316	0.133	22
Mean Number of Objects Visited during Exploration	-0.001	0.996	22
StDev of Objects Visited during Exploration	0.422	0.040*	22
Range of Objects Visited during Exploration	0.375	0.071	22

Table 5. Correlation coefficients for individual difference measures and angular AE in the shortcut test, for the 24 participants in the Free Walking group in Experiment 1.

Tables 5 and 6 and Figure 13 show the results of the correlations with just the Free Walking group. Absolute error in the Free Walking group was correlated with two measures of spatial abilities: PTSOT ($r_{22} = 0.469$, $p = 0.021$) and Road Map test ($r_{22} = -0.547$, $p = 0.006$). Performance was also correlated with the standard deviation of the number of objects visited during exploration ($r_{22} = 0.422$, $p = 0.040$) and was marginally correlated with the max-min score ($r_{22} = 0.375$, $p = 0.071$). VE in the Free Walking group was correlated with the Road Map test ($r_{22} = -0.448$, $p = 0.028$) and current video game use ($r_{22} = -0.413$, $p = 0.045$). It was also correlated with the two measures of evenness during exploration: Standard deviation of object visits ($r_{22} = 0.591$, $p = 0.002$) and Max-min score ($r_{22} = 0.566$, $p = 0.005$). The mean number of objects visited was

marginally correlated ($r_{22} 0.384$, $p = 0.064$). Interestingly, a greater number objects were visited on average tended to correspond to greater VE, yielding higher variable error.

	r	p-value	df
Age	0.179	0.403	22
SBSOD	0.315	0.134	22
PTSOT	0.278	0.189	22
Road Map Test	-0.448	0.028*	22
Current Video Game Use	-0.413	0.045*	22
Current Navigational Games	-0.350	0.093	22
Past Navigational Games	0.026	0.905	22
Nausea	-0.242	0.254	22
Immersion	0.050	0.821	22
Distance Traveled during Exploration	0.178	0.406	22
Total Angular Rotation during Exploration	0.002	0.992	22
Mean Number of Objects Visited during Exploration	0.384	0.064	22
StDev of Objects Visited during Exploration	0.591	0.002**	22
Range of Objects Visited during Exploration	0.566	0.005**	22

Table 6. Correlation coefficients for individual difference measures and VE of absolute angular error in the shortcut test, for the 24 participants in the Free Walking group in Experiment 1.

Comparing the overall correlations and the Free Walking correlations reveals a similar pattern of individual differences. Road Map scores, PTSOT errors, and the standard deviation of the number of objects visited during exploration were correlated with angular AE in both analyses. For VE, only the range of the number of objects visited during exploration showed up in both correlations, however, measures that were significant in one correlation were often marginally correlated in the other. In general the r values for the correlations were stronger in the Free Walking analysis. There may be more overall noise in the other experimental groups, so that these factors account for a smaller proportion of the variance in these groups, or some factors may affect performance differently in the different experimental groups.

Discussion

Experiment 1 examined the contributions of vestibular input, proprioception/motor information, and cognitive decision-making to learning survey knowledge of a novel environment. Participants learned a large room-sized hedge maze by walking, being pushed in a wheelchair, or watching a video. They either made decisions about where they explored the environment or were guided along paths matched to the Free Walking group. The results suggest that proprioceptive/motor information makes the largest contribution to survey learning, with the Walking groups performing significantly better than the combined Wheelchair and Video groups. In contrast, making decisions about exploration did not aid survey learning at any level of information. Men consistently had lower errors and were less variable than women throughout this experiment.

The results of this experiment point to lower errors and more consistent responses in the Walking groups than in the Wheelchair or Video groups. Mean AE were significantly lower in the Walking groups than in the Video groups, and marginally lower than the combined mean of the Wheelchair and Video groups. The VE of the absolute angular errors showed that the Walking group was significantly less variable than the combined mean of the Wheelchair and Video groups. Signed angular errors also revealed a similar trend. While there were no main effects of decision-making in any of the eight trial types, there were main effects of information in 4 of the trials types, and marginal effects in two more trial types. In all but one of the trial types, the Walking groups had the lowest signed angular errors.

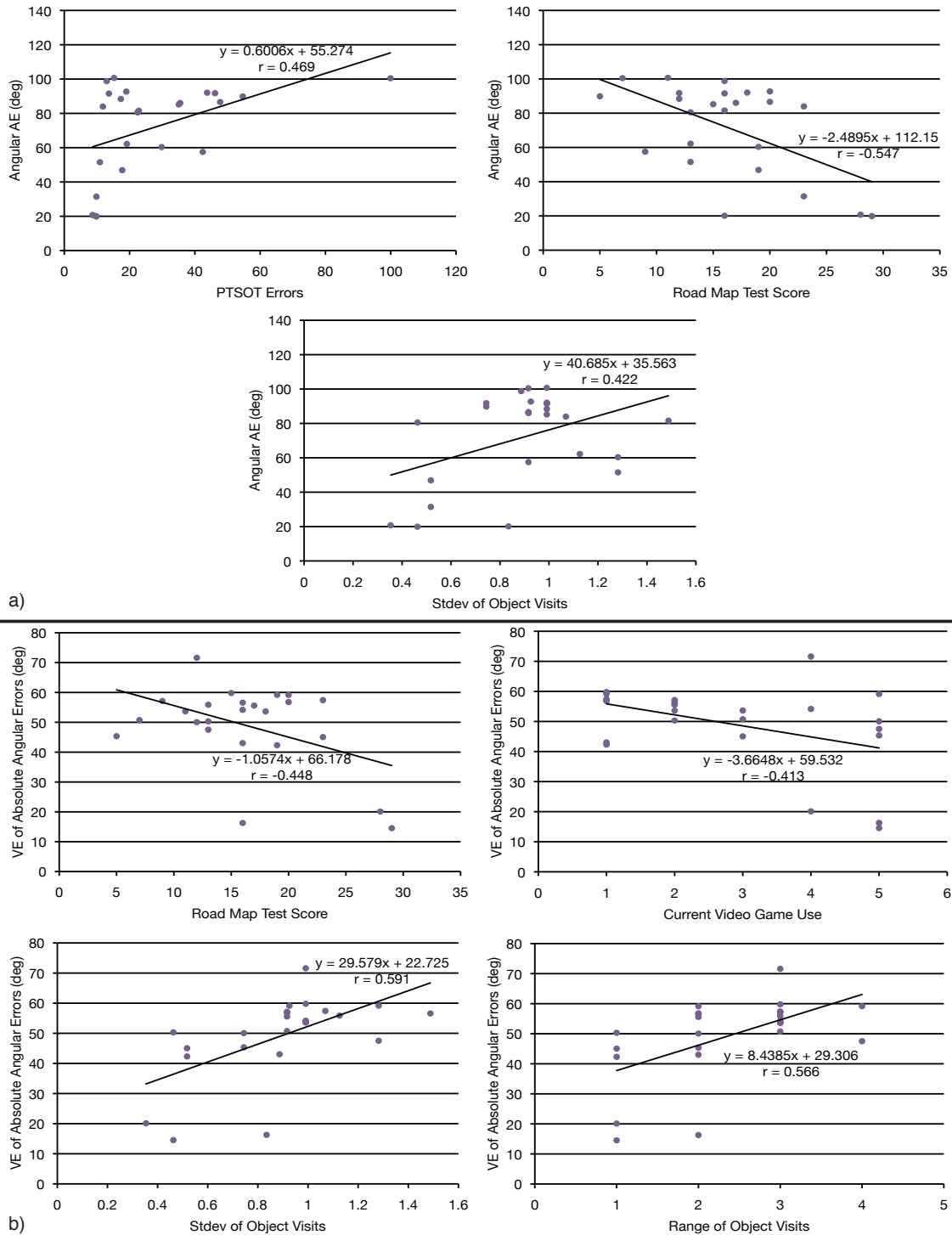


Figure 13. Correlations between performance in the shortcut test with individual difference measures for participants in the Free Walking group. Each data point represents the mean score for one participant. a) Significant correlations of angular AE with PTSOT errors, Road Map Test scores, and the standard deviation of the number of object visits during exploration. b) Significant correlations of the VE of absolute angular errors with Road Map Test scores, current video game use, the standard deviation of the number of object visits during exploration, and the maximum-minimum number of object visits during exploration.

Beyond the angular measures, the distances walked and final position errors also suggest that the Walking groups differed from the Wheelchair and Video groups. The VE of position error suggests that the Walking groups were less variable in their final position relative to the target than those in the Wheelchair and Video groups, likely as a result of the large angular VE in those two groups. Distance measures, when broken down by trial type, showed that the Walking groups tended to walk farther than the mean of the Wheelchair and Video groups. Walking further tended to make the Walking group more accurate for distances for most trial types. However, on some trials when the target was close to the start location, participants in the Walking groups overestimated that distance more than the other two groups. Item analysis found a significant effect of trial type on path length, suggesting that overall participants distinguished between the different trial types, and did not just respond randomly.

The measures associated with path length and final position must be considered with some caution, however. Only trials in which participants stayed within the tracking area of the lab were included in these analyses, leading to underestimates of path length and position error. While there were no group differences in terms of the number of times participants left the tracking area, some trial types tended to have more out of bounds trials than others, and some individuals tended to go out of bounds more often than others. Thus, data from these trial types or individuals might not reflect the full variability in responses. In addition, it is possible that leaving the tracking area could make participants more cautious, leading them to underestimate path lengths in general.

Finally, the analysis of the sketch maps revealed a somewhat different pattern of errors. While the Free Walking group drew the best sketch maps, those in the Guided

Video group also drew fairly accurate sketch maps. Overall, guided participants made better sketch maps, largely due to the Guided Video condition. This result is rather surprising, given that group's relatively poor performance in the shortcut task. Maps were scored based on the connections of the hallways, and the relative positioning of objects in relation to each other and the hallways, which participants may have learned without acquiring the metric distances and angles between objects. In that sense, the map drawing may be more indicative of route or graph knowledge, which will be discussed in Experiment 2. It is also possible that sketch maps are not appropriate tools for assessing survey learning, despite their frequent use in experiments examining survey knowledge.

The results of this experiment are consistent with the hypothesis that full idiothetic information from walking leads to the greatest survey knowledge. The most general finding was a reliable difference between the Walking condition (visual + idiothetic) and the Video condition (visual). The finding that the Walking condition was significantly better than the combined Video and Wheelchair (visual + vestibular) conditions suggests that proprioceptive/motor information may largely account for this advantage. Indeed, the Wheelchair condition tended to be closer to the Video condition, with no significant differences between them. Yet neither were there significant differences between the Wheelchair and Walking conditions. It is possible that the vestibular stimulation in the Wheelchair condition only loosely approximates that of walking, since the weight and center of mass in the wheelchair were different from walking, and the vestibular information might have been related to how the experimenter pushed the wheelchair. These differences could account for the lack of significant effects

between the Wheelchair and Video groups. Thus, the safest conclusion is that idiothetic information makes a significant contribution to the acquisition of survey knowledge.

The results are not consistent with the hypothesis that making decisions about exploration would lead to greater survey learning. Throughout the experiment, the effect of decision-making consistently showed no differences between the Free and Guided groups in the shortcut task. Making decisions during the learning phase did not lead to lower distance, direction, or position errors at any level of information. The only measure that showed a difference between the levels of decision-making was the sketch maps, with the Guided groups drawing better maps than the Free groups. However, the sketch maps and their scoring procedures may not be a good measure of survey knowledge. Thus, the conclusion is that decision-making does not make a significant contribution to the acquisition of survey knowledge.

One concern about the finding that performance was best in the Walking group is a possible effect of encoding specificity. Given that all groups walked in the shortcut test, it may appear that the Walking group was tested in the same context in which they learned the environment, while those in the Wheelchair and Video groups were tested in a different context. Thus, the Walking group may have benefited simply because walking in a virtual environment at test matches walking in a virtual environment during encoding. To a certain extent, this difficulty was unavoidable, because the shortcut test had to be equated across conditions, and the levels of information in the learning phase had to be manipulated. However, the context was actually quite different in the learning and test phases. Whereas learning was performed in the hedge maze, the shortcut test was performed in a desert environment. In addition, walking is a well-calibrated task,

and so it is expected that participants in all groups would be able to turn and walk with relative precision in the shortcut test.

The results of Experiment 1 confirm previous research that found an advantage for walking over other levels of information during survey learning. Waller et al. (2004) found that walking led to lower pointing errors than watching a video, in agreement with the findings of the present experiment. The results also agree with Ruddle et al. (2011a), who found that walking lead to lower pointing errors compared with video and physical rotations, although only in large-extent environments. Others research has suggested that vision may be sufficient for survey knowledge (Mellet et al., 2010; Waller & Greenauer, 2007); however, both Mellet et al. and Waller & Greenauer used fairly simple and symmetrical U-shaped hallways, which may be easier to learn than larger or more complex environments, and Mellet et al. trained participants to recall the sequence of landmarks in temporal order. Waller & Greenauer also found differences between their groups, but only when the path between the start location and target location was sufficiently complex. Those who walked had lower errors in those cases than those who were wheeled or watched a video. Thus, large and complex environments may reveal the contributions of idiothetic information more than small environments. If the path integration system is noisy compared to the visual information, then idiothetic information may not contribute much in a small environment compared to vision alone. However, in large or complex environments, visual path integration may become less accurate, and the contributions of proprioceptive/motor and vestibular information could become evident. Taken together, these results suggest that the proprioceptive

information available during walking makes a significant contribution to survey learning, especially in large or complex environments.

The contribution of vestibular input is less clear-cut. Chance et al. (1998) determined that physical rotations, even without physical translations, significantly contributed to survey learning, but only after three sessions of experience with the environment and task. In contrast, Ruddle et al. (2011a) found that physical rotations did not aid survey learning, while proprioceptive and motor input did, especially in large-scale environments. Waller et al. (2003) found that having a full field of view and the ability to turn the head while being driven on a route lead to better survey learning than even having matching inertial information but restricted head movements; the latter condition was no better than having mismatched vestibular input or purely visual information. On the other hand, the group with full FOV and free head turns was still riding in a car without any proprioceptive input, and thus, it appears that vestibular information might make some small contribution to their survey learning, but only when paired with additional information. Thus, the contribution of vestibular information appears to be small in comparison with that of proprioceptive/motor input.

The results of the present experiment found that the Wheelchair groups, which had vestibular information but no proprioceptive/motor input, tended to have errors closer to the Video groups, which only had visual information, than to the Walking groups. When combined with the Video condition in Helmert contrasts, the combined group was often significantly different from the Walking group in terms of direction and distance errors. However, the Wheelchair groups also did not tend to be significantly different from either the Walking or the Video groups individually. Taken together, the results of

Experiment 1 and previous research suggest that vestibular information is not sufficient for full survey knowledge, but it may make a small contribution beyond purely visual information. However, the vestibular information in a wheelchair or a car might not be the same as natural walking, and so the contribution of vestibular input could be larger than suggested by these experiments.

The results regarding the role of decision-making agree with previous research finding no advantage for active decision-making in survey learning. Earlier results have found inconsistent findings depending on the task and specific setup using desktop VR (e.g. Péruch et al., 1995; Wilson et al., 1997), and decision-making in a purely path integration task (Wan et al., 2010) are not relevant to spatial learning. In comparison to previous literature, this experiment was the first to systematically test this question of decision-making during natural walking with full idiothetic information, as opposed to desktop VR. Yet Experiment 1 found no evidence that active decisions about exploration conferred any benefit to survey learning at any level of information.

In addition to the primary experimental findings, Experiment 1 found large sex differences, with men outperforming women in most aspects of survey learning. Women also had lower scores on all of the measures of spatial ability, and also played fewer video games than men. It seems likely that differences in spatial abilities, rather than some aspect of the task, were behind the sex differences in the shortcut test, especially since several measures of spatial ability were correlated with performance. Previous research has found mixed results for sex differences in spatial navigation, with some determining that there are large sex differences (Moffat, Hampson, & Hatzipantelis, 1998; Waller, 2000; Wolbers & Hegarty, 2010). Others have found few differences or

that primary differences are related to specific types of spatial tasks, although route learning tends to be one of the tasks with similar performance (Castelli, Corazzini, & Geminiani, 2008; Coluccia & Louse, 2004). The results of the present experiment are consistent with the view that there are sex differences in spatial ability, although they do not reveal the sources of those differences. For example, spatial abilities may be susceptible to stereotype threat (Spencer, Steele, & Quinn, 1999), where 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 vary depending on the level of stereotype threat for spatial skills (Martins, Johns, Greenberg, & Schimel, 2006; McGlone & Aronson, 2006). Given that the present experiment was not designed to investigate sex differences and the procedure did not take specific steps to alleviate potential stereotype threat, it is possible that this was a factor in the observed differences.

Examination of individual trial types is also informative for understanding what survey knowledge participants learned acquired during learning. Some trial types were clearly easier than others for participants in the shortcut test, as indicated by bias in distance and direction errors. For example, participants seemed to have learned the directions from the well to the gear accurately, but underestimated the distance by quite a bit. In other cases, participants seemed to know that the target object was close to the start location, but did not have the correct direction, for example from the gear to sink. For certain trial types, nearly all participants turned in precisely the wrong direction, as when walking from the snowman to the rabbit. This finding suggests that participants generally had a consistent idea of where the target object was located, but this location

was incorrect. Participants tended to overshoot small distances and undershoot long distances, although the turn angles did not demonstrate a consistent pattern of errors. As will be seen in Experiment 2, these trial types gave participants trouble in the graph test, as well, with common errors appearing in both the shortcut and shortest path tests.

Finally, there were large individual differences in shortcut performance. Figure 3 indicates that even in the Free Walking group, which had full information and the ability to make decisions during exploration, only about half of the participants had absolute angular errors above chance. Many participants had clearly learned the relationships between some of the objects, as indicated by errors closer to 60 degrees, while only 3 participants had anything close to good survey knowledge, with absolute errors as low as 20 degrees. This finding suggests that humans are generally poor at making direct shortcuts. It is also possible the task was too difficult. Other studies that tested survey knowledge found absolute pointing errors ranging from near 0 for some target locations (Waller et al., 2003), to 20 degrees in other locations (Chance et al., 1998; Waller et al., 2004) to greater than 70 or even 100 degrees in other locations (Chance et al., 1998; Waller & Greenauer, 2007). The results of Experiment 1 fall within this range, although they are somewhat on the high end. The participants in those experiments also stood (or imagined standing) at one of the objects and pointed to another object. One difference between this experiment and those is the complexity of the maze environment. Participants started each trial by walking the branch hallway that contained the starting object, but these hallways often had one or two turns in them, which might have disoriented the participants relative to the overall maze structure. It is an open question

whether a maze without branch hallways would be easier for participants. Despite these high errors, differences between the groups still emerged in the shortcut test.

Performance was correlated with several individual difference measures. In particular, the mean absolute angular error correlated with the PTSOT and the Road Map Test. These two measures are particularly related to shifting perspective and mentally rotating point of view and had significant correlations in both the Free Walking group and the combined group. These findings suggest that the ability to mentally shift perspective is important to survey learning and especially the shortcut test. A participant might mentally align themselves with the view of the start object, and perhaps imagine their orientation with respect to the target object. Video game use also appeared to help somewhat in the precision of the shortcut test. Playing video games might involve learning environments from different perspectives, which could aid in survey learning or with perspective-taking during the shortcut test. In contrast, self-reported sense of direction (SBSOD) did not correlate with either of the performance measures. The SBSOD might tap into other types of spatial learning, such as graph learning. People rarely need to make difficult survey judgments about their environments, instead, a good sense of direction often means that a person can reach desired locations using roads, which is more similar to graph knowledge.

Additional measures of individual difference considered the influence of exploration on learning. Visiting objects more equally during the learning phase, as measured by the standard deviation of the number of visits per object and the range object visits, was correlated with both the mean and VE of absolute angular errors. These measures of evenness of exploration may be related to a person's ability to know where

they have explored and where they have not. A person with low evenness will tend to overexplore certain areas, while ignoring other regions of the maze. Interestingly, the two evenness measures were not correlated with PTSOT or Road Map Test over all participants, and only the range of object visits was correlated with Road Map Test scores in the Free Walking group ($r_{22} = -0.434$, $p = 0.034$). This result suggests that, at least under conditions of full information, some of the perspective-taking abilities are related to the ability to explore evenly, although that correlation could be due to a common cause and cannot entirely explain exploration behavior in this test.

The groups tended to be fairly even in their spatial abilities and their experiences with the experiment, as would be expected with random assignment. Most of the spatial abilities tests showed sex differences, as discussed earlier. In addition to sex differences, those who were guided had higher Road Map Test scores. The Video groups tended to play more video games than those in the Walking groups, possibly helping them with using the keyboard controls. Notably, there was a significant effect of information in the amount of nausea the participants experienced, with the Walking groups experiencing the least, then the Wheelchair groups, and the Video groups experiencing the most. While nausea ratings were not correlated with performance either overall or in the Free Walking group, it is possible that the increased nausea in the Wheelchair and Video groups hindered their performance by distracting them from attending to the task.

Finally, it should be noted that there was a significant effect of decision-making on evenness of exploration, such that those who made decisions during exploration had higher standard deviations of object visits than those who were guided. Given that the paths for the guided groups were matched to the Free Walking group, this effect was

driven by the difference between the Free Walking group and the Free Wheelchair and Free Video groups. Having less information, then, may affect participants' ability to keep track of where they have explored and where they have not, which in turn is related to performance on the shortcut test.

In sum, Experiment 1 demonstrates that having full idiothetic information, particularly proprioceptive/motor information, contributes significantly to the accuracy of survey knowledge. On the other hand, making decisions about exploration does not seem to significantly contribute to survey knowledge. It seems that full idiothetic information is not needed to reveal an effect of decision-making, since even with full information there were no differences between making decisions and being guided. The ability to mentally take different perspectives is correlated with performance, perhaps because it is useful in evenly exploring the environment. Thus, self-produced idiothetic information appears to be the primary component of active learning for survey knowledge. Experiment 2 explores learning in a somewhat easier test of spatial knowledge, graph knowledge.

Chapter 4

Experiment 2: Active and Passive Learning in a Test of Graph Knowledge

Introduction

As seen in Chapter 2, the question of active and passive spatial learning may depend on the type of spatial knowledge that is tested. Whereas Experiment 1 investigated active contributions to metric survey knowledge, Experiment 2 examines their role in acquiring graph knowledge. Graph knowledge is a somewhat stronger than route knowledge and but less metric than survey knowledge. The graph structure of an environment involves a network of place “nodes” linked by path “edges.” In contrast, route knowledge is a sequence of place-action associations. Active learning in a graph task may be related to learning how the sequences of places and actions combine into a larger network map. The purpose of Experiment 2 is to examine the contributions of idiothetic information and decision-making to graph knowledge.

Researchers typically test route knowledge by leading participants on a particular route, and then asking them to retrace parts of the route. Since Experiment 2 was designed to test the contribution of cognitive decision-making to graph knowledge, leading participants on a set route would prevent examination of this aspect. Thus, testing the contributions of active and passive navigation to graph knowledge requires a different approach than tests of route knowledge. In Experiment 2, participants were tested with a shortest route test, which required them to walk between different locations in a virtual maze, traversing routes they might not have taken during the learning phase. However, this type of test does not preclude route learning. Often participants repeated the same path from target to target; even if it was not the most efficient path, it was the path they knew. The shortest route task is simpler than the shortcut task used in Experiment 1 because participants do not need to know metric distances and angles

between locations to successfully complete the task. However, participants must integrate the specific paths traveled and locations visited during exploration into a network graph to take novel routes and detours, which requires more than route knowledge.

As discussed in Chapter 2, few prior experiments have examined the influence of active and passive exploration on the acquisition of route knowledge, and even fewer have examined graph knowledge. The combined research of Péruch and Wilson (Péruch et al., 1995; Péruch & Wilson, 2002; Wilson et al., 1997; Wilson, 1999) found inconclusive results when finding target objects in a semi-open environment, using desktop virtual reality. Tan et al. (2006) also used desktop VR, but found that controlling a joystick and making decisions about movement exploration lead to taking shorter paths to find target objects than watching a video. Likewise, Farrell et al. (2003) found that using a keyboard to make decisions in a desktop VR environment led to learning a route better than watching a video of a route, although neither Farrell et al. nor Tan et al. distinguished between the control of movement and making decisions, nor did they manipulate levels of information. Hazen (1982) found that children who made decisions about exploring were better at retracing routes and finding novel shortcuts, but found no advantage for walking over being carried. In contrast, Grant & Magee (1998) and Ruddle et al. (2011a, 2011b) found that information was key to learning a route, although neither examined the role of decision-making.

The lack of research on active and passive spatial learning in route or graph knowledge presents a clear gap in the literature. In particular, the role of cognitive decision-making has only been studied in desktop environments, without clear or

consistent findings. Decision-making may play a stronger role in graph knowledge than survey knowledge, because qualitative decisions could correspond to route choices in a graph. Experiment 2 specifically tested the interaction of decision-making during exploration with different levels of information. Experiment 2 fully crossed three levels of information—Walk, Wheelchair, and Video—with two levels of decision-making—Free and Guided—during exploration of a complex maze environment. Walking groups had full access to all idiothetic and visual information, the Wheelchair groups had access to vestibular and visual information, and the Video groups had access to vision alone. The Free groups were allowed to make decisions about where they moved during exploration, while the Guided groups were guided along paths matched to the Free Walking group. The test in Experiment 2 was the shortest route test, designed to assess graph knowledge. Participants in the shortest route test were required to walk in the maze corridors from one object to another object, taking the shortest route possible, with occasional blockers forcing them to take novel detours.

Despite the dearth of prior research, some theoretical predictions can be made. Route knowledge may be based on learning the place-action associations during the route (Siegel & White, 1975). Making decisions during exploration may aid in learning these associations, by drawing attention to the associations or allowing explorers to test predictions about what they are likely to encounter at each turn. Learning these associations for routes may assist in learning the graph structure of the environment. Thus, those participants who were free to make decisions during the learning phase were expected to perform better than those who did not make decisions. Because the graph knowledge is situated between route and survey knowledge, it is possible that idiothetic

information may also contribute to graph learning, or interact with decision-making. While graph learning does not require knowledge of metric distances and angles, idiothetic information could still aid graph knowledge to the extent that a graph incorporates rough metric information, such as distance labels on edges and angle information at nodes, which could provide a navigator additional opportunity to learn the graph structure of the environment.

The results of Experiment 2 suggest that cognitive decisions make a significant contribution to graph knowledge, and that information also interacts with decision-making. Those who both walked and made decisions about their exploration while learning had the greatest graph knowledge. Large individual differences were observed in all groups, and several measures were identified that predicted performance in the shortest route test.

Methods

Participants

Participants were recruited through advertisements and were paid for their time at the rate of \$8/hour. All participants signed forms indicating their informed consent to be a part of the study in fulfillment of the requirements of the Brown University IRB. 159 (85 female) people participated in the experiment. 19 (13 female) withdrew due to symptoms of simulator sickness, 6 (4 female) for failure to find all of the objects during exploration, and 6 (4 female) for experimenter error or technical problems. 128 participants (64 female) completed the experiment. Mean age of participants who completed the study was 22.89 (SD = 7.07). The dropout due to symptoms of simulator sickness for the experimental groups was: Free Walk, 1 (plus one failure to find all the

objects); Guided Walk, 3; Free Wheelchair, 1, Guided Wheelchair, 0; Free Video, 5 (plus 5 failures to find all the objects); Guided Video, 9.

Equipment

Equipment was the same as Experiment 1.

Environment

The maze environment was the same as in Experiment 1 (Figure 1).

Design

The design of the experiment involved 6 groups of participants in a 3 x 2 design (Table 1), with three levels of information (Walk, Wheelchair, Video) and two levels of decision-making (Free, Guided) during the learning phase. Each group consisted of 16 participants, randomly assigned with the restriction that the groups were evenly divided between males and females, for a total of 96 participants in this experiment. Sixteen additional participants were added to each of the two of the walking groups (Free Walking and Guided Walking), for a grand total of 128 participants.

Learning Phase

The six learning conditions were the same as in Experiment 1 (Table 1). The procedure during the learning phase was the same as in Experiment 1.

Test Phase

Graph knowledge was tested with a shortest route task, in which participants were instructed to walk from a starting object to a target object, within the corridors of the maze. Each trial began with the participant entering a branch hallway of the maze containing the starting object (approximately 1 meter from the object), to allow them to orient themselves. Starting the trial at the location of an object prevented the participant

from exploring the maze and gaining additional knowledge during the test phase. The participant walked into the starting object, and then the target object was named over the headphones. All objects were replaced with red blocks during the trial to avoid providing feedback (Figure 14), although the four landmark paintings remained visible during the task. The participant followed the corridors of the maze to reach the target object location, taking the shortest route possible, and was given 30 seconds to reach the target location. The trial ended when the participant clicked the mouse to indicate that they thought they had reached the target object, or the 30 seconds elapsed. The maze then disappeared, and the experimenter wheeled the participant to the starting location of the next trial, taking a circuitous route. This task probed graph knowledge in that participants were asked to travel between objects that were not necessarily directly traveled during exploration. Position and orientation were recorded throughout the trial, with the location of the mouse click serving as the endpoint for the trial.

In addition, occasional “detour” trials were included in the test phase. The detour trials blocked one of the shortest paths with a barrier, and participants were instructed to find a novel route to the desired object (Figure 14). These catch trials provided a second test of graph knowledge by requiring participants to synthesize new routes in the maze in order to quickly find a detour. Proportion of correct catch trials were compared with direct trials and were compared between groups. Because the barrier often required additional time and distance to travel around, participants were given 15 additional seconds for these trials, although they were not informed of the additional time.

Multiple dependent measures were taken for each trial, and analyses of all measures were included for completeness. (1) The proportion of correct target locations

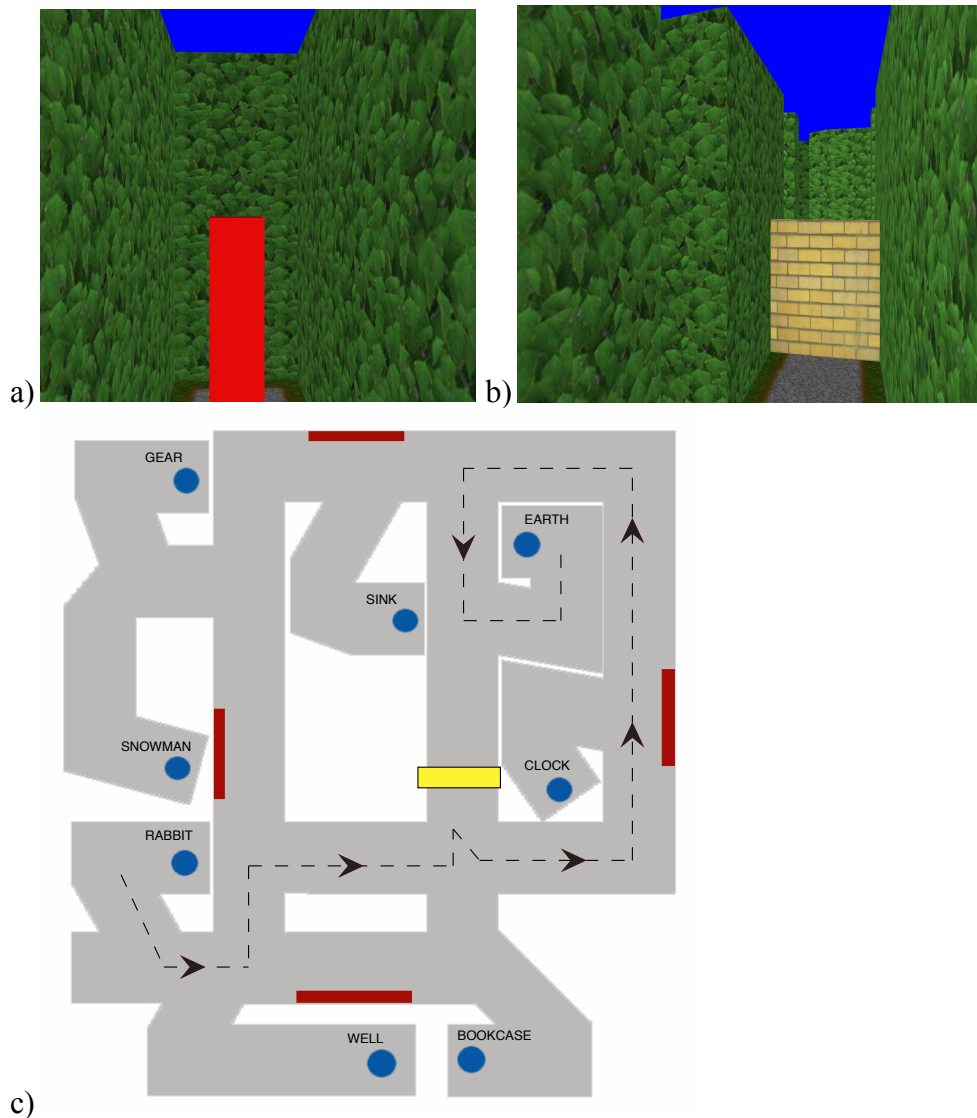


Figure 14. Views of the test phase in Experiment 2. a) Red blocks replaced the objects during the test trials. b) A wall was placed in a hallway during detour trials. c) Overhead view of the maze with an example of a detour trial, from the rabbit to the earth. A participant taking the correct path would walk toward the earth, encounter the wall, and then take a new path to reach the target location.

was measured, where a trial was considered correct if the participant ended the trial anywhere in the branch hallway of the target object. (2) Consistency measured the proportion of trials within the same trial type in which the participant chose the same location (even if not the correct target). (3) Path length measured the total distance traveled during the trial. (4) Distance from target measured the straight-line distance from the target location at the end of the trial. (5) Travel time measured the time from walking

into the staring object until the mouse was clicked or time elapsed. (6) The proportion of “out-of-time” trials was measured. (7) Participants drew sketch maps of the maze after the test phase. These sketch maps were scored on a 1-10 scale by a rater that was not familiar with the hypotheses or the experimental conditions. Correlation analysis was also performed on several individual differences measures and performance in the shortest route task.

In the shortest route task 8 trial types were used, with each trial type consisting of one pair of objects, using the same object pairs as Experiment 1. There were 5 total trials per trial type, 3 were direct trials and 2 were detour trials, for a total of 40 trials. All trials were presented in a random order with the exception that trial types did not repeat back-to-back. Although the experimental groups received differing levels of information during the learning phase of the experiment, they all performed the test phase with full visual, vestibular, proprioceptive, and motor information as in Experiment 1.

Procedure

The procedure was the same as Experiment 1. Participants were given practice with the virtual environment, then they had 10 minutes of exploration during the learning phase, with the instructions to “Find all the objects and learn their locations.” Participants then completed 2 practice trials, followed by 40 experimental trials in the test phase. Finally, participants were taken out of virtual reality, where they drew a map of the maze, answered several questionnaires, and took the Road Map Test and the PTSOT spatial abilities tests (Appendix 1).

Analysis

For each dependent measure, values for each participant were averaged over all

40 trials combining over detour and direct trials. Detour and direct trials were also examined separately. The exceptions to combining over all 40 trials were consistency, which examined how often participants went to an object for a given trial type, analysis of the detour trials, and analysis of the proportion correct of the first and last ten trials. Most comparisons were made with a 3x2x2 (information x decisions x sex) unequal-n ANOVA. Analyses of proportion data were also performed using an arcsine transformation, however, there were no substantial differences between those analyses and those of the non-transformed data. Thus, analyses of the non-transformed data are reported here.

Chance was defined as being at the location of one of the 8 objects at the end of a trial, or $1/8 = 0.125$. One might think that participants would not end up at the same object where they started the trial, making chance somewhat higher, however, that did happen on occasion. In addition, participants could end a trial in one of the hallways, such as when time expired, and so chance could also be somewhat lower. Thus, the $1/8$ level for chance was deemed to be an appropriate intermediate value.

Results

Proportion Correct

Preliminary analysis. Preliminary analysis was performed using 16 participants per group, for a total of 96 participants. Mean proportion correct was analyzed using a 3x2x2 (information x decisions x sex) ANOVA. Means for the six groups were: Free Walking (mean = 0.607, SD = 0.292); Guided Walking (mean = 0.459, SD = 0.323); Free Wheelchair (mean = 0.297, SD = 0.219); Guided Wheelchair (mean = 0.518, SD = 0.305); Free Video (mean = 0.479, SD = 0.311); Guided Video (mean = 0.384, SD =

0.248). There was a significant effect of sex ($F_{1,94} = 6.023$, $p = 0.016$, $\eta_p^2 = 0.067$) and a significant information x decision-making interaction ($F_{2,93} = 3.981$, $p = 0.022$, $\eta_p^2 = 0.087$). Men tended to have a higher proportion of correct trials than women.

Participants in the Free Walking group had the best performance, while those in the Free Wheelchair had the worst performance.

Examination of the results suggests that the information x decision-making interaction may be driven primarily by the poor performance in the Free Wheelchair condition. In contrast, the Guided Wheelchair condition had similar performance to the other guided groups in the experiment. The two Wheelchair groups were removed in order to more clearly examine the interaction of decision-making with visual and idiothetic information. In a 2x2x2 (information x decisions x sex) ANOVA using just the Walking and Video groups, a main effect of sex was found ($F_{1,62} = 4.949$, $p = 0.030$, $\eta_p^2 = 0.081$), with men performing better than women. There was also a marginal effect of decision-making ($F_{1,62} = 2.794$, $p = 0.100$, $\eta_p^2 = 0.048$), such that those who made decisions during the learning phase performed better than those who were guided. These initial results suggested a possible effect of decision-making that was worth exploring further. Thus, 16 additional participants were added to both the Free and Guided Walking groups. The remainder of the analyses were conducted with unequal-n ANOVAs, with 32 participants in the Free and Guided Walking groups, and 16 participants in the Free Wheelchair, Guided Wheelchair, Free Video, and Guided Video groups, for a total of 128 participants.

Final analysis. Results for overall proportion correct with 128 participants are shown in Figure 15. The dashed line indicates chance performance. Analysis of the

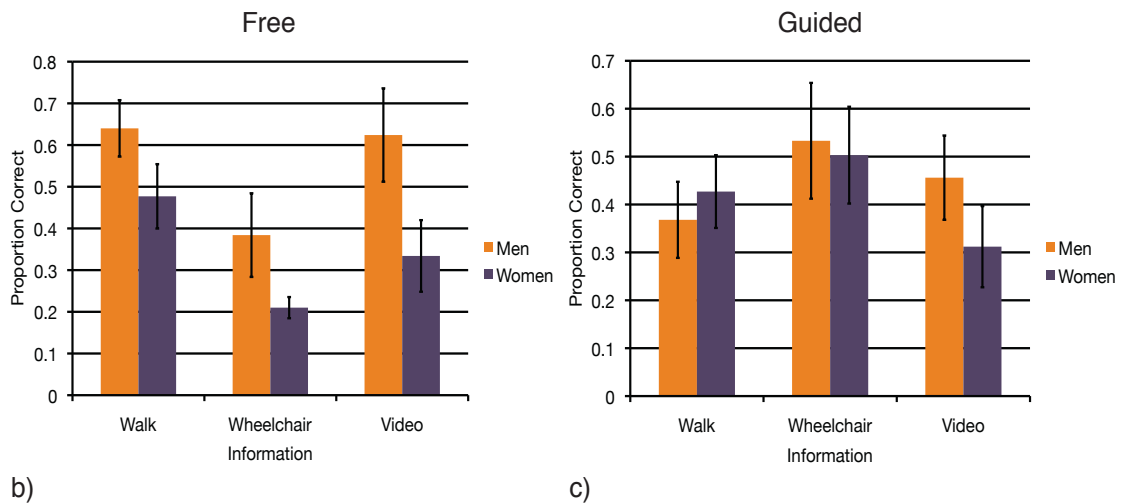
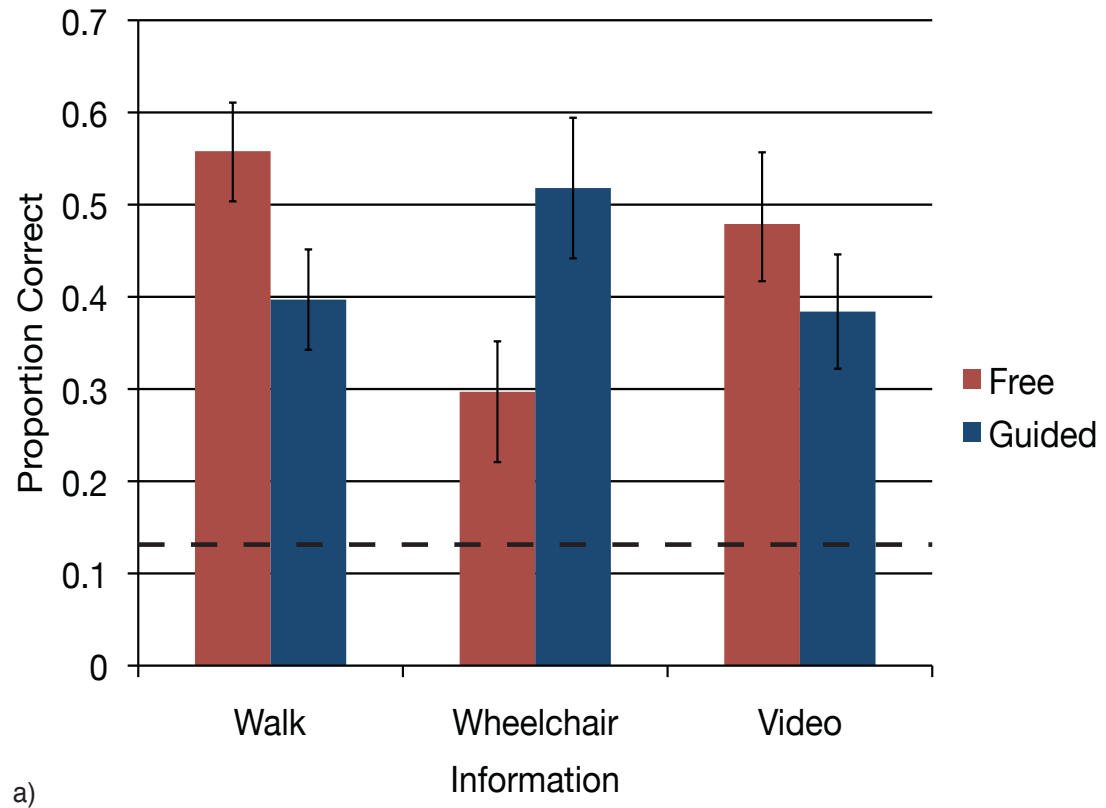


Figure 15. Proportion of trials ended at the correct object location. Dashed line indicates chance level. a) Proportion correct of the six experimental groups. b) Proportion correct of the three Free experimental groups broken down by sex. c) Proportion correct of the three Guided experimental groups broken down by sex.

proportion of correct trials was conducted using a 3x2x2 (physical x decisions x sex) unequal-n ANOVA. The ANOVA revealed a main effect of sex ($F_{1,126} = 5.454$, $p = 0.021$, $\eta_p^2 = 0.045$) and an information x decision-making interaction ($F_{2,122} = 4.943$, $p = 0.009$, $\eta_p^2 = 0.079$). Men were more accurate than women. The Free Walking group had the highest proportion correct, and the Free Wheelchair had the lowest. None of the other main effects or interactions were significant. In general, all groups performed above chance in this experiment.

As with the equal-n analysis, the information x decision-making interaction appeared to be driven by the poor performance in the Free Wheelchair group. The two wheelchair conditions were removed from the analysis in order to provide a clearer examination of the interaction of decision-making with visual and idiothetic information. This analysis again found a main effect of sex ($F_{1,94} = 4.609$, $p = 0.035$, $\eta_p^2 = 0.050$), and also a main effect of decision-making ($F_{1,94} = 4.157$, $p = 0.044$, $\eta_p^2 = 0.045$). Men performed better than women, and those who made decisions during the learning phase had a higher proportion correct than those who were guided during the learning phase. Interestingly, there was no main effect of information ($F_{1,94} = 0.548$, $p = 0.461$, $\eta_p^2 = 0.006$). A planned comparison between the two walking groups (Free Walking, Guided Walking) yielded a significant effect of decision-making ($F_{1,62} = 4.568$, $p = 0.037$, $\eta_p^2 = 0.071$), with the Free Walking group having a greater proportion of correct trials than the Guided Walking group. This result indicates that with full idiothetic information, making decisions about exploration significantly affects performance in the shortest route task. The comparison between the two video groups (Free Video, Guided Video) did not show

an effect of decision-making ($F_{1,30} = 1.035$, $p = 0.318$, $\eta_p^2 = 0.036$), but did have a main effect of sex ($F_{1,30} = 5.426$, $p = 0.027$, $\eta_p^2 = 0.162$).

Figure 16 illustrates the individual performances of the two walking groups. In this figure, the participants were organized according to performance rank, such that the lowest performing participants are on the left, and highest performers are on the right. A Mann-Whitney U Test evaluated the rankings of the proportion correct in the two groups, and found that the rankings were significantly different ($U = 341.5$, $p = 0.022$).

Qualitative assessment of these patterns reveals that participants in both groups had the capacity to perform both extremely poorly or extremely well. This large performance range highlights the individual differences that abound in navigation tasks. The patterns also suggest that making decisions about exploration does not differentially affect performance at one end or the other of the spectrum, but instead provides an overall boost for those who actively make decisions about their exploration, such that an average participant in the Free Walking group learned the locations of one or two more objects than their guided counterparts.

Consistency

Consistency of choosing the same target location was designed to be analogous to be a measure of the reliability of route choice, analogous to standard deviation. There were five repeats of each trial type during the shortest route task. Consistency was computed as the frequency of the most commonly selected location, even if it was incorrect (with a maximum of 5). Participants' final consistency score was the average of the eight trial types (Figure 17a).

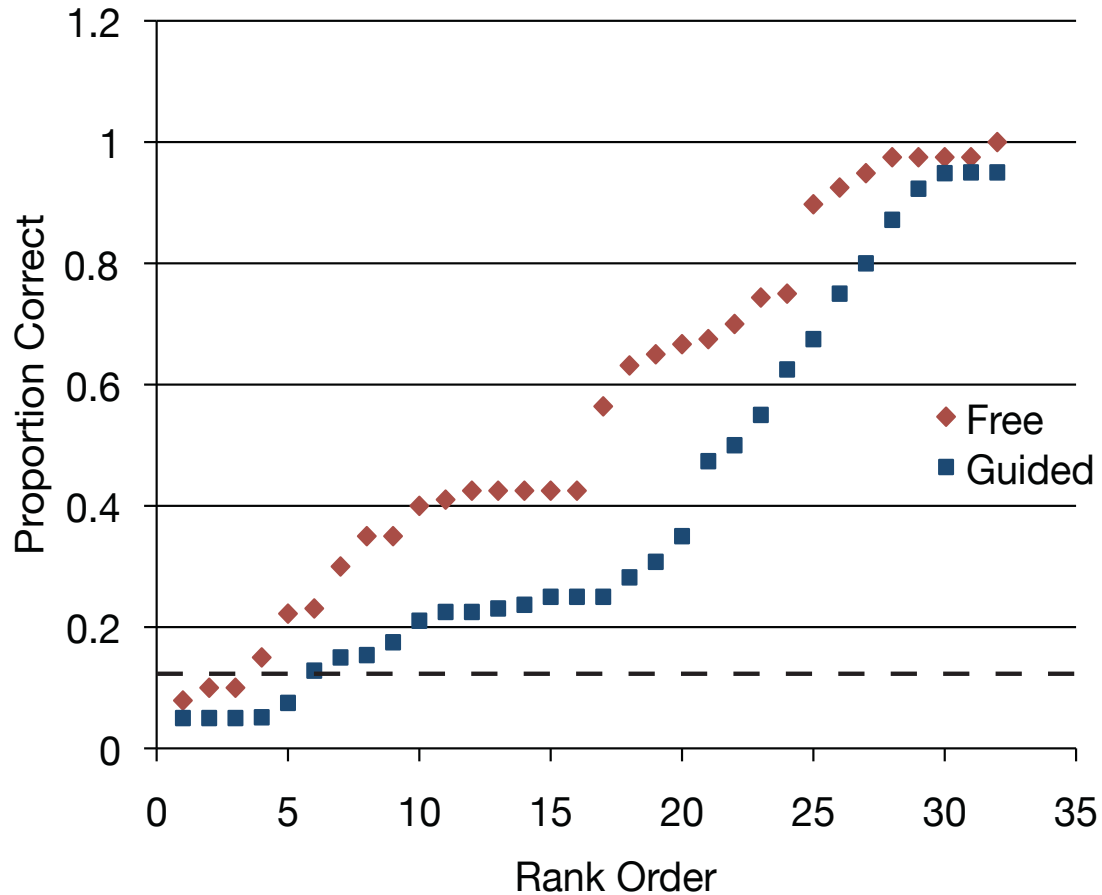


Figure 16. Individual performance in the Free Walking and Guided Walking conditions. Participants in each group were ordered from least proportion correct to great proportion correct. Dashed line indicates chance level, 0.125.

For object consistency, a 3x2x2 ANOVA (information x decisions x sex) found a main effect of sex ($F_{1,122} = 5.598$, $p = 0.020$, $\eta_p^2 = 0.046$), with men being more consistent than women. There was also an information x decision-making interaction ($F_{2,122} = 5.123$, $p = 0.007$, $\eta_p^2 = 0.081$). The interaction mirrors that of proportion correct, where the Free Walking group was most consistent, and the Free Wheelchair was the least.

As with proportion correct, the planned contrast between the Free and Guided Walking groups was examined in more detail. In this comparison, the main effect of

decision-making was marginally significant ($F_{1,62} = 3.869$, $p = 0.054$, $\eta_p^2 = 0.061$), with the Free Walking group tending to be more consistent than the Guided Walking group.

Path length

Path length measured the cumulative distance traveled by the participant during the course of the trial. For mean path length, there was only a marginal information x sex interaction ($F_{2,122} = 2.617$, $p = 0.077$, $\eta_p^2 = 0.043$), with men in the video condition tending to walk further. There were no effects of the standard deviation of path length.

The mean path length comparison for the two walking groups only showed a marginal effect of sex ($F_{1,62} = 3.027$, $p = 0.087$, $\eta_p^2 = 0.048$), with men walking somewhat shorter paths than women, and no effects for the standard deviation of path length.

Distance from target

Distance from target was calculated as the straight-line distance between the participant's location at the end of the trial and the actual location of the target. This measure might reflect that a participant knew the general direction or region of the target, but did not choose the correct target (Figure 17b). The 3x2x2 ANOVA (information x decisions x sex) found a main effect of sex ($F_{1,126} = 4.498$, $p = 0.036$, $\eta_p^2 = 0.037$) and an information x decision-making interaction ($F_{2,122} = 4.828$, $p = 0.010$, $\eta_p^2 = 0.077$). Men tended to be closer to the target object, and those in the Free Walking group were closest to the target object, and those in the Free Wheelchair furthest away.

Distance from target also showed a main effect of decision-making in the comparison between Free and Guided Walking ($F_{1,62} = 4.450$, $p = 0.039$, $\eta_p^2 = 0.069$),

with the Free Walking group ending closer to the target at the end of the trial than the Guided Walking group.

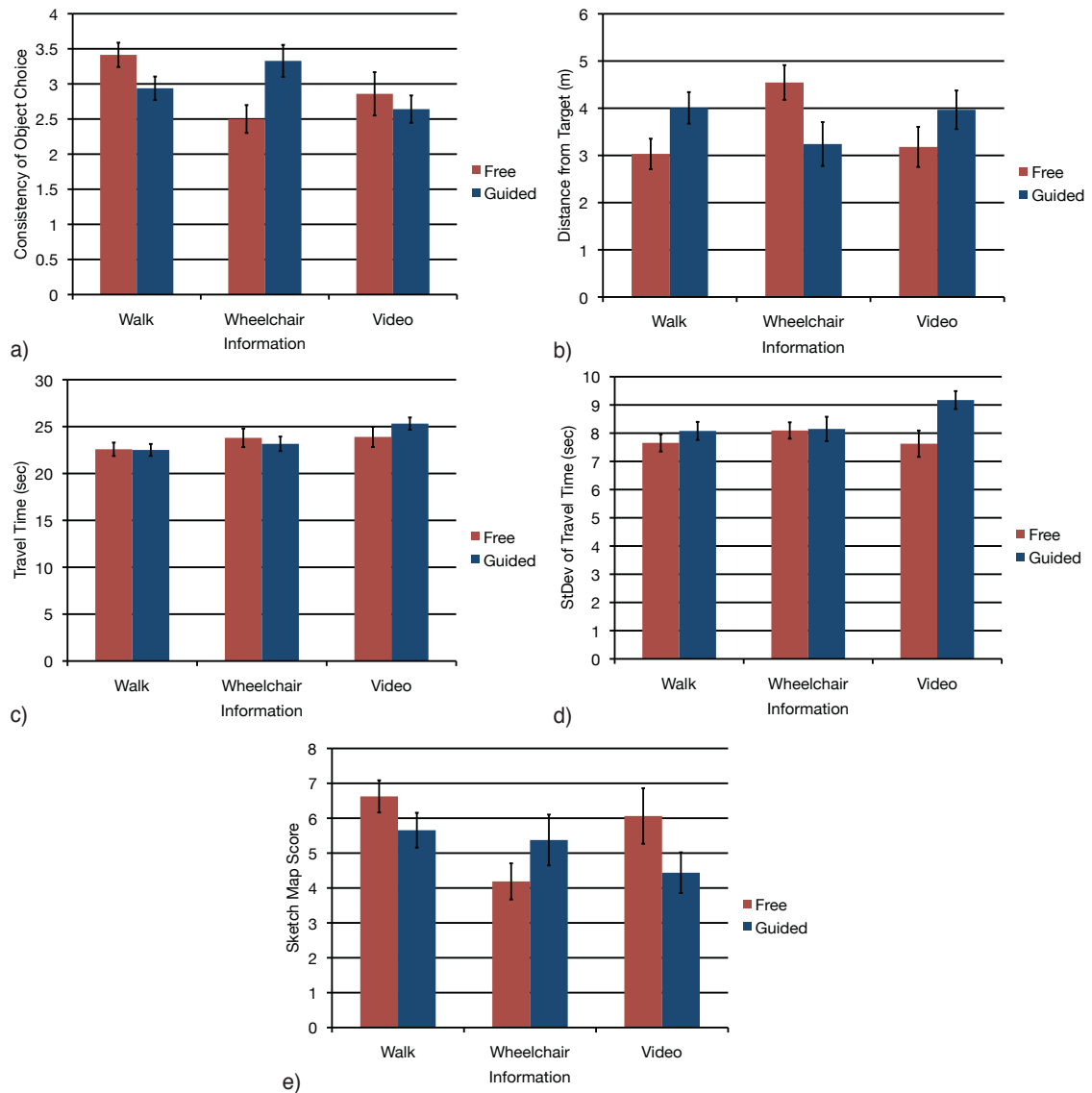


Figure 17. Additional results from Experiment 2. a) Consistency of object choice. b) Distance from target at the end of the trial. c) Mean travel time. d) Standard deviation of travel time. e) Sketch map scores.

Travel time

The time taken to select the target was measured, starting from the time the participant entered the starting object and ending at the end of the trial. This response time was capped at the 30-second time limit. There was a main effect of sex ($F_{1,126} =$

6.923, $p = 0.010$, $\eta_p^2 = 0.056$), with women taking more time than men. There was also a main effect of information ($F_{2,125} = 3.517$, $p = 0.033$, $\eta_p^2 = 0.057$). Post-hoc Tukey HSD comparisons showed that those who walked spent less time traveling than those in the video groups ($p = 0.026$). The standard deviation of travel time showed a main effect of decision-making ($F_{1,126} = 4.751$, $p = 0.031$, $\eta_p^2 = 0.039$). Those who did not make decisions during the learning phase were more variable in their response time than those who made decisions (Figure 17c and 17d).

When comparing just the Free and Guided Walking groups, average travel time also had a significant main effect of sex ($F_{1,62} = 4.486$, $p = 0.038$, $\eta_p^2 = 0.070$), with women taking more time than men. There were no effects of the standard deviation of travel time for these two groups.

Out of time

The out of time measure indicated the number of trials that the 30-second time limit expired. There were only marginal effects of information ($F_{2,125} = 2.605$, $p = 0.078$, $\eta_p^2 = 0.043$) and sex ($F_{1,126} = 2.859$, $p = 0.094$, $\eta_p^2 = 0.024$), women tending to run out of time more often than men, and those in the Video group running out of time marginally more often than those in the Walking group ($p = 0.062$).

There was only a marginal effect of sex when comparing the two walking groups ($F_{1,62} = 3.184$, $p = 0.079$, $\eta_p^2 = 0.050$), with women tending to run out of time more often.

Map scores

The sketch maps that participants drew after the test phase were scored on a 1-10 scale by a rater that was not familiar with the hypotheses or the experimental conditions. Results of the map drawing analysis are shown in Figure 17e. A 3x2x2 (information x

decisions x sex) unequal-n ANOVA found a main effect of information ($F_{2,125} = 3.201$, $p = 0.044$, $\eta_p^2 = 0.052$) and a decision-making x sex interaction ($F_{1,124} = 4.455$, $p = 0.037$, $\eta_p^2 = 0.037$). There was also a marginal effect of sex ($F_{1,126} = 3.931$, $p = 0.050$, $\eta_p^2 = 0.033$), a marginal information x decision-making interaction ($F_{2,122} = 2.628$, $p = 0.077$, $\eta_p^2 = 0.043$) and a marginal information x sex interaction ($F_{2,122} = 2.546$, $p = 0.083$, $\eta_p^2 = 0.042$). Post-hoc Tukey tests showed that those in the Walking groups drew significantly better maps than those in the Wheelchair groups ($p = 0.048$). Men tended to draw better maps than women; women in the Free Wheelchair group drew especially poor maps.

Examination of map drawing in the two Walking groups found only a marginal decision-making x sex interaction ($F_{1,60} = 3.638$, $p = 0.061$, $\eta_p^2 = 0.057$), with men in the Guided Walking group drawing fairly poor maps compared to men in the Free Walking group. Women drew maps of approximately equal quality in both Free and Guided Walking groups.

Detours

Approximately 40% of the trials were “detour” trials, where a wall was placed in one of the hallways. Participants did not necessarily encounter the wall during trials, however, performance may have been affected by having to take a novel route if they did encounter the wall (Figure 18). Detour trials were analyzed with regard to the proportion of correct trials.

For trials without detours (direct trials), there was a main effect of sex ($F_{1,126} = 4.694$, $p = 0.032$, $\eta_p^2 = 0.039$) and a significant information x decision-making interaction ($F_{2,122} = 4.467$, $p = 0.014$, $\eta_p^2 = 0.072$). There was also a marginal decision-making x sex interaction ($F_{1,124} = 2.808$, $p = 0.096$, $\eta_p^2 = 0.024$). Men performed detours

better than women, and those in the Free Walking group had a greatest proportion correct on detour trials, while the Free Wheelchair group had the lowest proportion. For trials with detours there was also a significant main effect of sex ($F_{1,126} = 5.932$, $p = 0.016$, $\eta_p^2 = 0.049$) and an information x decision-making interaction ($F_{2,122} = 5.557$, $p = 0.005$, $\eta_p^2 = 0.087$), with the relative ordering of the groups the same as the detour trials. The effects of sex and the interaction between information and decision-making were somewhat stronger when detours were present, suggesting that the detours do provide a more stringent test of spatial learning.

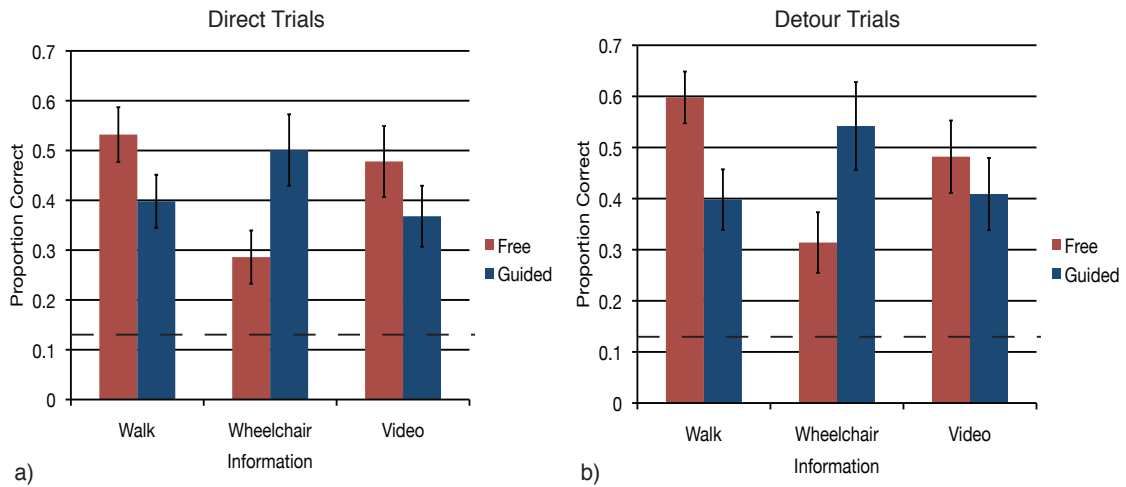


Figure 18. Proportion correct of direct and detour trials in Experiment 2. Dashed line indicates chance level. a) Proportion correct of the direct trials for the six experimental groups. b) Proportion correct of the detour trials for the six experimental groups.

Analysis of detour and direct trials was also conducted on the two Walking and two Video groups. A 2x2x2 ANOVA (information x decision x sex) on direct trials revealed a main effect of sex ($F_{1,94} = 4.354$, $p = 0.040$, $\eta_p^2 = 0.047$) and a marginal effect of decision-making ($F_{1,94} = 3.855$, $p = 0.053$, $\eta_p^2 = 0.042$), but no main effect of information or interactions. Analysis of the detour trials revealed a significant main effect of sex ($F_{1,94} = 4.365$, $p = 0.040$, $\eta_p^2 = 0.047$) and a main effect of decision-making ($F_{1,94} = 4.490$, $p = 0.037$, $\eta_p^2 = 0.049$), but no main effect of information or interactions.

This result suggests that there is no interaction between decision-making and idiothetic information when participants are required to rely more on their graph knowledge of the environment.

Likewise, for the comparison between the Free and Guided Walking groups, it appears that the advantage of decision-making is similar in both detour and direct trials. For trials with detours, there was a significant main effect of decision-making ($F_{1,62} = 6.551$, $p = 0.013$, $\eta_p^2 = 0.098$), while in the trials without detours the difference between the two groups was marginal ($F_{1,62} = 3.147$, $p = 0.081$, $\eta_p^2 = 0.050$). In both cases, the Free Walking group had a greater proportion correct than the Guided Walking group. Thus, the detours proved more difficult for those who did not make decisions about their exploration than for those who made decisions. The Free Walking group actually performed somewhat better in the detour trials than in the direct trials, perhaps because there was extra time to locate the target; however, the Guided Walking group was unable to take advantage of this extra time.

Learning during test

While care was taken to reduce the amount of information about the layout of objects in the maze that was available during the test phase, it is possible that learning could have occurred during the course of testing, and this experience may have affected the experimental groups in different ways. Although none of the objects were present during the test trials, a savvy participant might notice the locations of the landmarks (paintings) after they were dropped off at the starting object. In addition, participants walked through the hallways during the test phase, giving them additional information about the path structure of the maze.

A one-way ANOVA compared the proportion correct in the first ten trials with the last ten trials. This analysis revealed a significant effect of trial group ($F_{1,254} = 21.847$, $p < 0.001$, $\eta_p^2 = 0.079$), such that the target was located correctly more often in the last ten trials than in the first ten. It is of interest to determine if the pattern of results is altered by experience during testing. Thus, the proportion correct in the first ten trials and last ten trials of the test phase were examined separately (Figure 19).

Both the first ten trials and last ten trials showed a main effect of sex (First ten: $F_{1,126} = 4.156$, $p = 0.044$, $\eta_p^2 = 0.035$; Last ten: $F_{1,126} = 6.727$, $p = 0.011$, $\eta_p^2 = 0.055$) and a significant information x decision-making interaction (First ten: $F_{2,122} = 4.677$, $p = 0.011$, $\eta_p^2 = 0.075$; Last ten: $F_{2,122} = 3.610$, $p = 0.030$, $\eta_p^2 = 0.046$). Men had a greater proportion correct than women. Those in the Free Walking and Guided Wheelchair groups tended to do better in the first ten trials than the other groups. A significant decision-making x sex interaction was found only during the last ten trials ($F_{1,124} = 5.620$, $p = 0.019$, $\eta_p^2 = 0.046$). Men and women in the Guided groups performed equally well. However, men who made decisions during the learning phase performed better than those who were guided, while women who made decisions performed somewhat worse than those who were guided.

A separate analysis of the Free and Guided Walking groups also revealed a significant effect of decision-making for the first ten trials ($F_{1,62} = 5.464$, $p = 0.023$, $\eta_p^2 = 0.083$), with the Free Walking group having a greater proportion correct than the Guided Walking group. By the last ten trials, the difference between the two groups was only marginal ($F_{1,62} = 2.950$, $p = 0.091$, $\eta_p^2 = 0.047$). These results could indicate that without

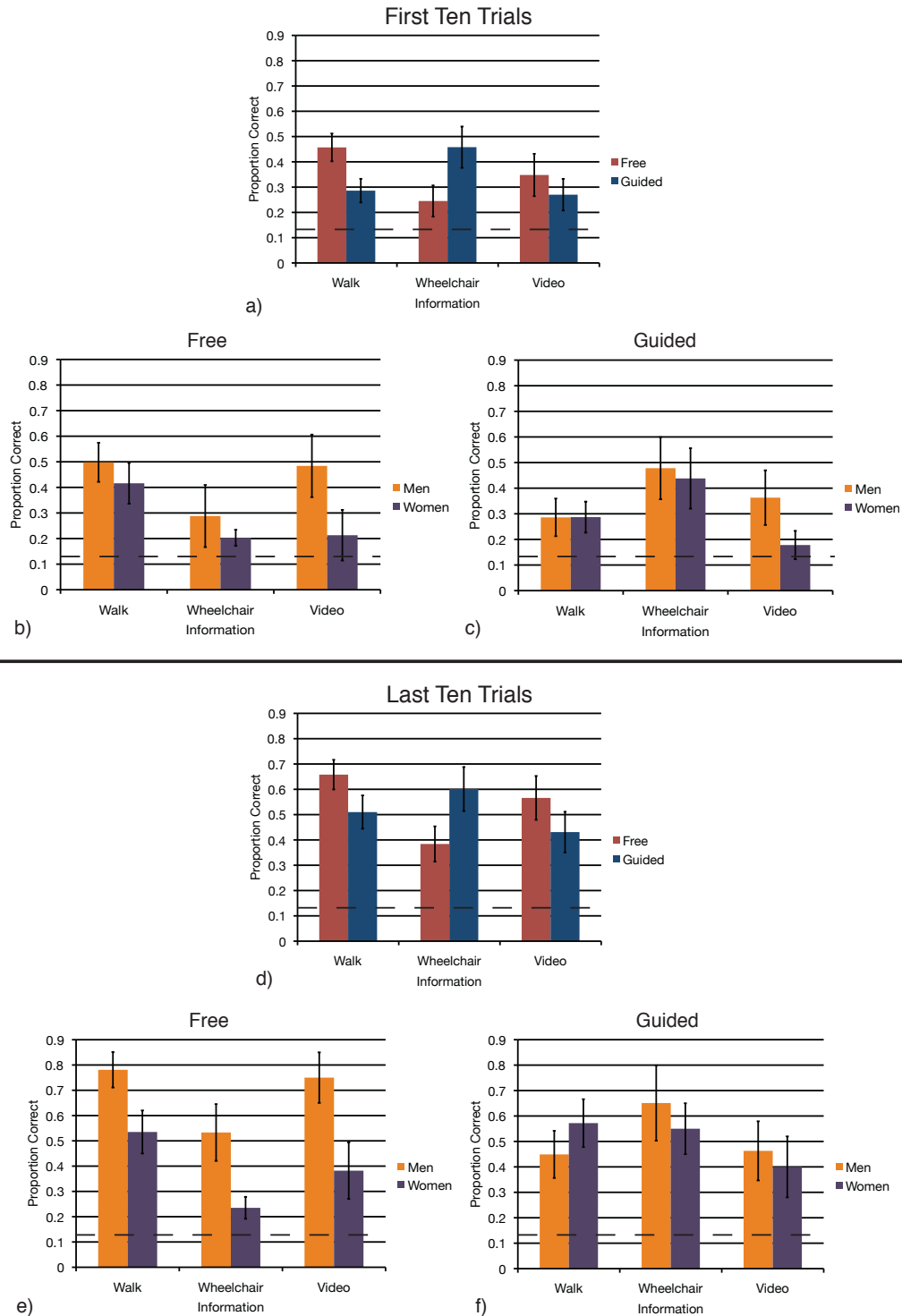


Figure 19. Proportion correct of (top) the first ten trials and (bottom) the last ten trials of Experiment 2. Dashed line indicates chance level. a) Proportion correct of the first ten trials for the six experimental groups. b) Proportion correct of the first ten trials of the Free conditions separated by sex. c) Proportion correct of the first ten trials of the Guided conditions separated by sex. d) Proportion correct of the last ten trials for the six experimental groups. e) Proportion correct of the last ten trials of the Free conditions separated by sex. f) Proportion correct of the last ten trials of the Guided conditions separated by sex.

having had much opportunity to learn more about the maze, the effect of decision-making was even more prominent.

There was also a significant decision-making x sex interaction ($F_{1,60} = 4.567$, $p = 0.037$, $\eta_p^2 = 0.071$) in the proportion correct of the last ten trials for the Walking groups. Women in both the Free and Guided groups performed similarly in the last ten trials. In contrast, men in the Free Walking group performed better than the women in that group, and men in the Guided group performed worse than women in that group, leading to a large effect of decision-making for men.

Trial types

To analyze the different trial types, an item analysis with a repeated-measures ANOVA was performed on the proportion of correct trials, with trial type as a within-subject factor, and information, decision-making, and sex as between-subjects factors. The ANOVA revealed a significant main effect of trial type ($F_{7,121} = 9.548$, $p < 0.001$, $\eta_p^2 = 0.076$), a significant main effect of sex ($F_{1,126} = 5.585$, $p = 0.020$, $\eta_p^2 = 0.046$) and a significant information x decision-making interaction ($F_{2,122} = 4.886$, $p = 0.009$, $\eta_p^2 = 0.078$). Post-hoc tests of the trial types found that trial type 7 (snowman to rabbit) was the most difficult, with only 35.04% correct, while trial type 8 (bookcase to well) was the easiest, with 58.63% correct. One-way ANOVAs comparing each trial type to chance (0.125) revealed that all trial types were correctly located significantly more often than chance (all p -values < 0.001). This result suggests that participants were distinguishing between trial types during Experiment 2.

Individual differences

The large individual differences highlighted in Figure 16 warrant further consideration. First, it must be established that the groups did not differ on measures of spatial ability that might affect the outcome of the experimental manipulations. Second, it is of interest to determine what spatial measures correlate with performance on the shortest route task.

The spatial ability measures were the same as those used in Experiment 1: age, SBSOD Scale, PTSOT errors, Road Map Test Scores, current video game usage, current use of 1st person navigational video games, past use of 1st person navigational video games, nausea rating, immersion rating, distance traveled during exploration, mean number of times visiting each object during exploration, standard deviation of the object visits during exploration, and the range of object visits during exploration. As in Experiment 1, it should be noted that the exploration paths of the Guided groups were matched to those of the Free Walking group, and so their exposure to the maze is likely to be similar to that group, although their responses to these measures might differ.

Group differences. The first analysis of individual differences was aimed at determining whether the experimental groups were equivalent on these measures. This step insures that the random assignment of participants did not somehow lead to one group having higher spatial abilities than the others. 3-way ANOVAs (information x decisions x sex) were performed on the 7 measures of spatial abilities and experience.

Participants were generally of the same age; there was only a marginal information x decision-making interaction ($F_{2,122} = 2.443$, $p = 0.091$, $\eta_p^2 = 0.040$).

The three tests of spatial abilities showed similar patterns. For the SBSOD, there was a significant sex difference ($F_{1,126} = 12.475$, $p = 0.001$, $\eta_p^2 = 0.097$) and a decision-

making x sex interaction ($F_{1,124} = 3.918$, $p = 0.050$, $\eta_p^2 = 0.033$). Women gave worse self-report ratings for sense of direction, especially those in the Free decision-making groups. There was a marginal effect of sex in the PTSOT ($F_{1,126} = 3.658$, $p = 0.058$, $\eta_p^2 = 0.031$), but there was a main effect of information ($F_{2,125} = 3.411$, $p = 0.036$, $\eta_p^2 = 0.056$). Post-hoc Tukey HSD tests showed that participants in the two Video conditions had better performance on the PTSOT than those in the Walking groups. This result could account for the reduced effect of idiothetic information observed in Experiment 2. The Road Map Test showed a significant sex difference ($F_{1,126} = 12.796$, $p = 0.001$, $\eta_p^2 = 0.099$), again with men out-performing women.

The three video game measures primarily revealed sex differences. For current video game use, there was a significant sex difference ($F_{1,126} = 9.912$, $p = 0.002$, $\eta_p^2 = 0.079$), with men playing more video games than women. For both current and past use of navigational video games, there were only sex differences (current: $F_{1,126} = 6.527$, $p = 0.012$, $\eta_p^2 = 0.053$; past: $F_{1,126} = 12.011$, $p = 0.001$, $\eta_p^2 = 0.094$).

Thus, most of the group differences in spatial ability reflect sex differences, with men generally having greater spatial abilities and experience with video games than women. This difference in abilities and experiences could account for the sex differences observed in the shortest route test. Video game experience often involves learning the layout of a complex environment, and more experience with video games could facilitate learning the graph structure of the environment.

Finally, the Free and Guided Walking groups were compared using a 2 x 2 (decisions x sex) ANOVA parallel to the analysis of the shortest route data. Similar sex differences were observed in the spatial measures, with SBSOD, Road Map Test, current

video game use, and current navigational video games showing significant sex differences in the Free and Guided Walking groups. There was a marginal difference in age between the Free and Guided Walking groups ($F_{1,62} = 3.915$, $p = 0.052$, $\eta_p^2 = 0.061$), as well as a marginal difference in PTSOT errors ($F_{1,62} = 3.847$, $p = 0.054$, $\eta_p^2 = 0.060$) and past navigational video game experience ($F_{1,62} = 3.391$, $p = 0.071$, $\eta_p^2 = 0.053$). Notably, older participants also tended to have worse PTSOT scores and somewhat less past video game experience. To investigate these group differences further, the ANOVA was performed again on the proportion correct in the Free and Guided Walking conditions, treated PTSOT as a covariate. This eliminated the main effect of decision-making ($F_{1,62} = 2.416$, $p = 0.125$, $\eta_p^2 = 0.039$), as did treating age as a covariate ($F_{1,62} = 2.239$, $p = 0.140$, $\eta_p^2 = 0.037$). However, the main effect of decision-making remained during the first ten trials, before additional learning could take place, even when treating PTSOT as a covariate ($F_{1,62} = 4.030$, $p = 0.049$, $\eta_p^2 = 0.064$), as it did for the detour trials ($F_{1,62} = 4.170$, $p = 0.046$, $\eta_p^2 = 0.066$). Covarying age with the proportion correct of the first 10 trials rendered the decision-making effect marginal on both the first ten trials ($F_{1,62} = 3.829$, $p = 0.055$, $\eta_p^2 = 0.061$), and on the detour trials ($F_{1,62} = 3.803$, $p = 0.056$, $\eta_p^2 = 0.061$). Finally, covarying out PTSOT in the combined Walking and Video analysis of overall proportion correct also rendered the effect of decision-making marginal ($F_{1,94} = 3.633$, $p = 0.060$, $\eta_p^2 = 0.040$). These additional analyses suggest that a portion of the decision-making effect was due to somewhat lower spatial abilities in the Guided Walking group, an effect of decision-making still remains, as revealed in the first ten trials and the detour trials. This result implies that those with good perspective-taking abilities can take greater advantage of free decision-making. Perspective-taking could be

important during the learning phase, because a navigator might be able to link different parts of the maze from different perspectives together into the larger path structure, and during the test phase, because a navigator might be able to update routes in the graph when starting from different locations or encountering detours.

Differences in VR experience. Analysis of VR experience provides a way of examining whether certain conditions were associated with different experiences. For example, it is possible that experiencing the virtual world through a video may lead to weaker feelings of immersion. 3-way ANOVAs (information x decisions x sex) were performed on the 7 measures of VR experience.

There were sex differences in nausea ratings ($F_{1,126} = 17.709, p < 0.001, \eta_p^2 = 0.132$), with women giving significantly higher ratings for nausea, and an information x sex interaction ($F_{2,122} = 11.567, p < 0.001, \eta_p^2 = 0.166$). Women in the Walking groups tended to give lower nausea ratings than in the Wheelchair or Video groups. There was also a marginal difference between the three levels of information ($F_{2,125} = 2.514, p = 0.085, \eta_p^2 = 0.042$), where those in the Walking groups experienced the least nausea. Experiencing nausea could distract participants from learning the environment, and this might account for women's lower performance in the Wheelchair and Video conditions. This finding could be an important source of sex differences.

For immersion ratings in VR, there was only a marginal sex difference ($F_{1,126} = 3.519, p = 0.063, \eta_p^2 = 0.029$), with men giving somewhat higher immersion ratings than women.

For the total distance traveled during the learning phase, there was a significant difference between the three levels of information ($F_{2,125} = 4.842, p = 0.010, \eta_p^2 = 0.077$).

Post-hoc Tukey HSD comparisons found that those in the Video conditions traveled farther than those in the Walking conditions. There was also a main effect of information on the total angular rotations during exploration ($F_{2,125} = 14.313$, $p < 0.001$, $\eta_p^2 = 0.198$), as well as a sex difference ($F_{1,126} = 4.922$, $p = 0.028$, $\eta_p^2 = 0.041$) and an information x decision-making interaction ($F_{2,122} = 7.751$, $p = 0.001$, $\eta_p^2 = 0.118$). Post-hoc tests revealed that all three levels of information differed from each other. Those who walked had the greatest head rotation, while those in the wheelchair—especially those in the Free Wheelchair condition—turned their heads the least. Women also turned their heads less than men.

There was a main effect of information on the number of objects visited during the learning phase ($F_{2,125} = 5.383$, $p = 0.006$, $\eta_p^2 = 0.085$). Post-hoc Tukey HSD tests revealed that those in the Video groups visited more objects than those in the Wheelchair conditions. There was also a significant information x decision-making interaction ($F_{2,122} = 7.222$, $p = 0.001$, $\eta_p^2 = 0.111$). The Free Wheelchair group tended to visit the fewest number of objects during the learning phase.

For the measures of evenness of exploration during the learning phase, there was a significant difference between the two levels of decision-making ($F_{1,126} = 6.507$, $p = 0.012$, $\eta_p^2 = .053$) on the standard deviation of the number of objects visited. There were also a marginal information x decision-making interaction ($F_{2,122} = 3.030$, $p = 0.052$, $\eta_p^2 = 0.050$). For the range of objects visited, there was a difference between the two levels of decision-making ($F_{1,126} = 8.669$, $p = 0.004$, $\eta_p^2 = 0.070$). In general, those who freely explored tended to explore less evenly than those who were guided. However, since the Guided groups were matched to 16 participants of the Free Walking group, this main

effect of decision-making appears to be driven by the Free Wheelchair and especially the Free Video groups. The groups may be different in some spatial ability related to the evenly exploring, or the available information may in fact contribute to participants' ability to explore more evenly. This finding may have implications for learning the environment, since evenness of exploration is correlated with performance, as described below.

The measures related to differences in VR experience were also examined in just the Free and Guided Walking groups with a 2x2 ANOVA performed on the 7 measures. There was a difference between the groups on the amount of angular rotation during the learning phase ($F_{1,62} = 5.329$, $p = 0.024$, $\eta_p^2 = 0.082$), with those who made decisions turning their heads more.

Correlations with performance. To investigate what spatial abilities correlate with performance on the shortest route task, two approaches were taken. The first analysis combined performance of all 128 participants from all groups. This approach provides large statistical power to detect small effects. However, combining over all groups ignores any effects of the experimental manipulations. The second analysis focused on the Free Walking group, with full idiothetic information and the ability to make cognitive decisions about exploration. Examination of the Free Walking group provides a closer look at individual differences under close-to-normal exploration conditions. Because the dependent variable of proportion correct proved to be the primary performance measure on the shortest route test, with the other measures showing similar patterns, it was the focus of the correlation analysis.

Results of the overall correlations appear in Table 7 and Figure 20. These results indicate that a number of spatial measures were correlated with proportion correct, regardless of the experimental manipulation. Age ($r_{126} = -.243$, $p = 0.006$), self-reported sense of direction ($r_{126} = -.258$, $p = 0.003$), PTSOT perspective-taking errors ($r_{124} = -.332$, $p < 0.001$), Road Map Test score ($r_{125} = .243$, $p = 0.006$), and current general video game use ($r_{126} = .347$, $p < 0.001$) were all significantly correlated with performance in the shortest route test. Fewer of the measures related to the participants' experiences in the virtual environment correlated with performance. Self-reported ratings of immersion in VR ($r_{125} = .184$, $p = 0.038$) and the two measures of evenness of exploration, standard deviation of the number of objects visited during the learning phase ($r_{126} = -.232$, $p = 0.009$) and the range of the number of objects visited ($r_{126} = -.244$, $p = 0.005$) correlated with performance on the shortest route task.

	r	p-value	df
Age	-0.2430	0.006**	126
SBSOD	-0.2583	0.003**	126
PTSOT	-0.3317	<0.001***	124
Road Map Test	0.2430	0.006**	125
Current Video Game Use	0.3474	<0.001***	126
Current Navigational Games	0.1551	0.080	126
Past Navigational Games	0.1280	0.150	126
Nausea	-0.110	0.216	126
Immersion	0.1843	0.038*	125
Distance Traveled during Exploration	-0.0777	0.383	126
Total Angular Rotation during Exploration	0.1278	0.152	125
Mean Number of Objects Visited during Exploration	-.0179	0.841	126
StDev of Objects Visited during Exploration	-0.2312	0.009**	126
Range of Objects Visited during Exploration	-0.2444	0.005**	126

Table 7. Correlation coefficients for individual difference measures and proportion correct in the shortest route test, combined over all 128 participants in Experiment 2.

Examination of Figure 20 suggests that many of the correlations were driven by a small number of outliers, who were the worst performers. For example, the correlation

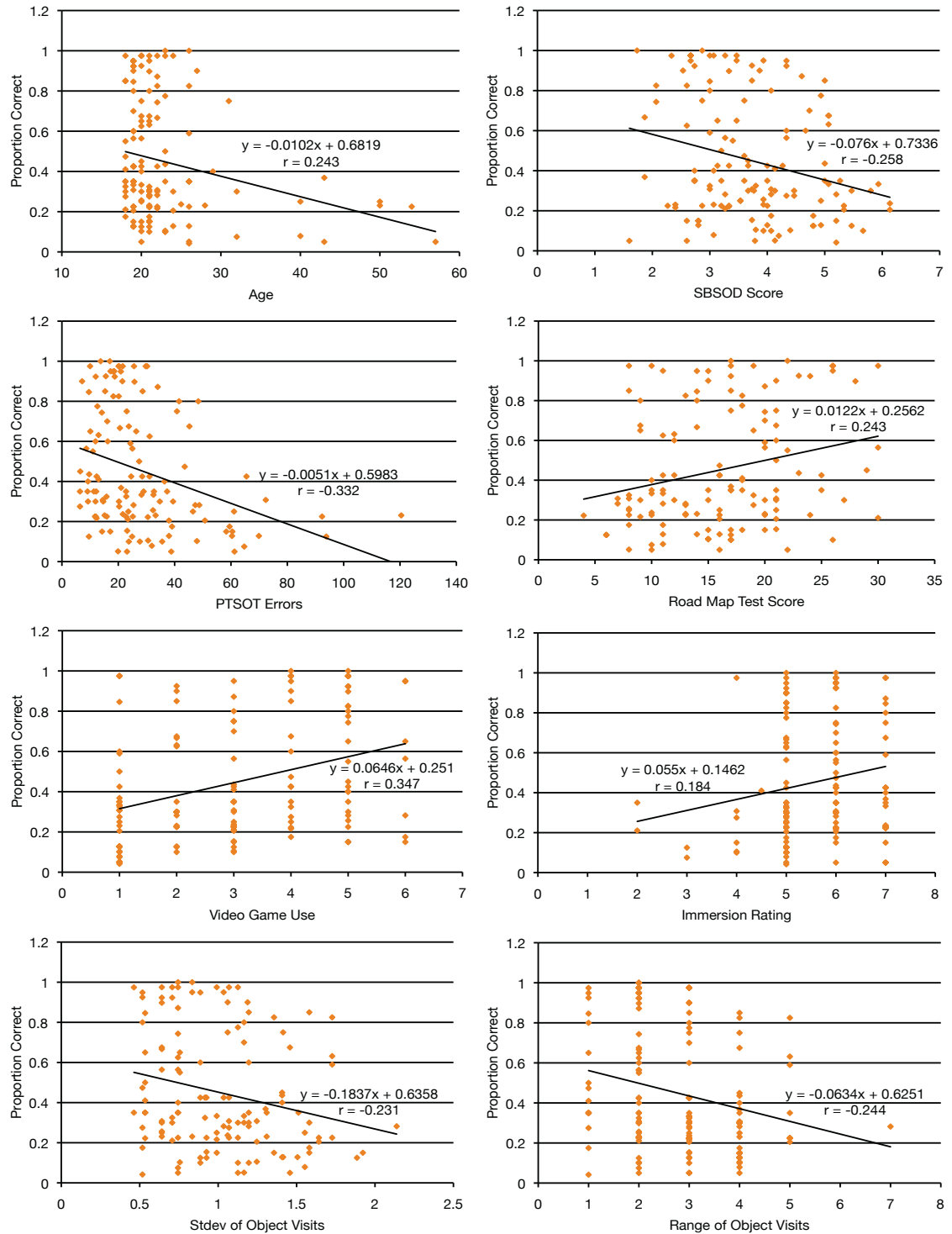


Figure 20. Significant correlations between 8 individual difference measures and proportion correct for all participants in all groups. Each data point represents the mean score for one participant. Correlations are for Road Map Test scores, SBSOD Scale, Age, PTSOT errors, current video game use, VR immersion ratings, the standard deviation of the number of object visits during exploration, and the range of object visits during exploration.

with age appears driven by those participants aged 40 or older. Similarly, PTSOT score appears to be driven by the relatively few participants who had very large errors of 45 degrees or more. Age, SBSOD, PTSOD, immersion, standard deviation of the objects visited, and the range of objects visited all tended to be driven by outliers in these measures, who also tended to perform poorly on the shortest route test. In general, it appears that these individual difference measures predicted when a participant did particularly poorly, but not necessarily when they did well. For example, a participant can have a highly even exploration pattern and was equally likely to do well or do poorly, but with a very uneven exploration pattern the participant was unlikely to do very well.

Table 8 and Figure 21 show the correlations between proportion correct in the Free Walking group and a number of spatial ability measures. The only measures that correlated with performance in the Free Walking group were the standard deviation of the number of object visits during the learning phase ($r_{30} = -.368$, $p = 0.038$) and the range of the number of object visits ($r_{30} = -.422$, $p = 0.016$), both measures of how evenly the participant explored their environment. Since they were both negatively correlated, this result suggests that the more unevenly a participant explored the environment, the less they learned about it. The Santa Barbara self-report on sense of direction scale (SBSOD) was marginally correlated with performance ($r_{30} = -.325$, $p = 0.070$), with those with a better sense of direction performing better in the shortest route test.

Overall, the magnitudes and signs of the correlation coefficients for the Free Walking group are similar to those for all participants. Nausea ratings and the current use of navigational video games were not correlated in either analysis. This finding implies that nausea likely does not account for poorer performance by women. Interestingly, the

level of VR immersion is not at all correlated in the Free Walking group, but is correlated with the overall correlation of all 128 participants. Notably, the total distance traveled, total angular rotation during exploration, and mean number of objects visited during exploration were not significantly correlated in either the overall correlation or the Free Walking group. However, the two measures of evenness are significantly correlated in both comparisons, with the correlation somewhat stronger in the Free Walking group. These measures were also correlated in the Guided Walking group (Stdev of object visits: $r_{30} = -0.321$, $p = 0.073$; Range of object visits: $r_{30} = -0.414$, $p = 0.018$), suggesting that guiding participants along a particularly uneven exploration path may similarly affect a participant's ability to learn the environment.

	r	p-value	df
Age	-0.2093	0.251	30
SBSOD	-0.3248	0.070	30
PTSOT	-0.2944	0.102	30
Road Map Test	0.2098	0.249	30
Current Video Game Use	0.213	0.242	30
Current Navigational Games	-0.0784	0.670	30
Past Navigational Games	0.2641	0.144	30
Nausea	0.2443	0.178	30
Immersion	0.0054	0.977	30
Distance Traveled during Exploration	0.1850	0.311	30
Total Angular Rotation during Exploration	0.0527	0.774	30
Mean Number of Objects Visited during Exploration	-0.1633	0.372	30
StDev of Objects Visited during Exploration	-0.3678	0.038*	30
Range of Objects Visited during Exploration	-0.4215	0.016*	30

Table 8. Correlation coefficients for individual difference measures and proportion correct in the shortest route test, for the 32 participants in the Free Walking group in Experiment 2.

Discussion

The results of Experiment 2 allow for several main conclusions to be drawn about active contributions to learning the graph structure of the environment. First, whereas decision-making during exploration did not contribute to survey learning in

Experiment 1, the data from Experiment 2 indicate that it significantly contributes to graph learning. This result is consistent with the hypothesis that making decisions about which path to take should facilitate the linking of paths and places in a graph. Second, this effect appears to depend on the information available, for decision-making played a stronger role in the presence of idiothetic information than with vision alone.

Unexpectedly, there was also an interaction between decision-making and information in the Wheelchair condition. Third, there is a highly reliable sex difference, with men performing the shortest route task more successfully than women.

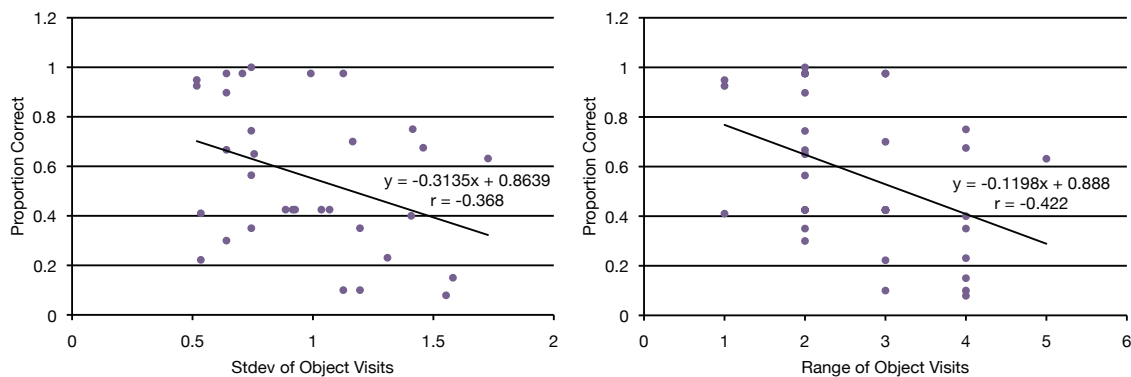


Figure 21. Significant correlations between 2 individual difference measures and proportion correct for the Free Walking group. Each data point represents the mean score for one participant. Correlations are for the standard deviation of the number of object visits during exploration, and the range of object visits during exploration.

First, the results of Experiment 2 suggest that decision-making significantly contributed to graph learning. Those in the Free Walking group were most accurate and consistent in the shortest route task. When directly comparing the two Walking groups, the Free Walking group had a greater proportion of correct trials than those in the Guided Walking group. Making decisions during exploration may have aided in learning place-action associations by drawing attention to the associations. Furthermore, making decisions during the learning phase allowed explorers to test predictions about what they

might encounter at each turn. Decision-making could provide a means for reinforcement learning to occur through the choices that the navigator made.

As noted in the introduction, little prior research has directly investigated the effects of information and decision-making on wayfinding, route, or graph tasks. Those who have studied the effects of decision-making either found an advantage for active decision-making (Farrell et al., 2006; Péruch et al., 1997; Tan et al., 2006), or found inconclusive effects (e.g. Péruch & Wilson, 2002). However, these studies were also conducted in desktop virtual reality, removing much of the idiothetic information about self-motion. There was a clear advantage for making decisions in the Walking groups, for both men and women. This result agrees with those of Hazen (1982), who found that children learned routes better when making decisions about their exploration while walking.

Close examination into some of the detailed aspects of the experiment also proved informative about active learning of graph information. Detour trials exaggerated the effects of the experimental manipulations. This effect was especially pronounced when considering the comparison between the Free and Guided Walking groups. On detour trials, the Free Walking group performed significantly better than the Guided Walking group, while this difference was only marginal on direct trials. These results suggest that the Free Walking group was able to find novel routes to the correct target location when they encountered a detour. The Guided Walking group, on the other hand, was unable to find the correct target when they had to take a novel route. Perhaps the Guided group had only learned one set route to the correct object, and when encountering the detour wall

they were unable to generate alternative routes based on more complete graph knowledge of the environment.

Analysis of learning during the course of the testing phase revealed similar patterns to those of the detour trials. The Free and Guided Walking groups showed a significant difference in the proportion of correct trials on the first ten trials, while the difference was not significant for the last ten trials. This result indicates that before much additional learning could take place in the test phase, the advantage of making decisions was particularly dramatic. After spending some time in the test phase, the Guided Walking group was able to neutralize some of the active advantage. Overall, all groups were able to learn the locations of some of the objects in the maze, although they did not improve equally. For example, women in the Free Wheelchair group learned very little during the course of testing, while men in the Free Walking group learned quite a bit. These results are difficult to generalize, as the differences between some groups became larger over the course of testing, while others became smaller.

Sketch maps showed a similar pattern of errors to the overall results, but were less strong than the overall proportion correct. This finding may be related to learning during the course of testing. Sketch maps were drawn at the end of the test phase, and as we have seen, the proportion correct on the last ten trials showed fewer group differences than the proportion correct on the first ten trials. Thus, the map drawing analysis is likely to reflect a similar pattern of results as the last ten trials.

There were also large differences when examining the different trial types in the experiment. Participants were able to reach all targets at greater than chance level, indicating that they were not simply randomly selecting the target. The particulars of the

trials may also be informative. The easiest target, the well, was fairly close to the start location of the trial, and was both near a landmark painting and the alcove in which it was situated had a distinctive shape. In contrast, the rabbit was the most difficult to find. While it was fairly close to a painting, the alcove shape was almost identical to those of three other objects. Indeed, participants tended to go more often to the incorrect gear location than to the correct rabbit location, since the gear shared the same alcove shape and was closer to the start location. The types of errors that participants made suggests that they may have occasionally relied on a view-based strategy, using the shape and orientation of the alcove to assist them when they were unable to use the graph structure of the maze to navigate. It is possible that a view-based navigation system may serve as a back-up system or as an alternate strategy to learning locations in a complex environment.

The second main conclusion of Experiment 2 is that the effects of decision-making appear to be more prominent in the presence of idiothetic information. In Experiment 2, the two Video groups were not significantly different in the proportion of correct trials. The Video group also took more time to reach the target location than the Walking group. It is possible that the Free Video condition relied more on video game experience than other conditions, since participants had to use a keyboard to control their movements, and men had more video game experience than women. The Video groups also had lower PTSOT errors than the Walking groups, possibly accounting for the reduced effect of idiothetic information in Experiment 2. These interactions illustrate why it has been difficult to draw conclusions from the results of previous research. Without complete idiothetic information, and potential interactions related to video game

experience, it could be difficult to determine the effects of making decisions. This result may indicate that any effect of decision-making may be most pronounced in the presence of full idiothetic information. Ruddle et al. (2011a) found that participants traveled less distance when walking during a target search task than when standing and making physical rotations. That result also suggests that full idiothetic information aids wayfinding when participants freely explore.

The effects of information were somewhat mixed in this experiment. Grant and Magee (1998) and Ruddle et al. (2011b) found an advantage for walking in route learning, but lead participants on a prescribed path, and neither put people in a wheelchair. The results of the Experiment 2 showed no overall effect of information, but rather had an interaction with decision-making. While previous research has examined either information or decision-making, few have explored both factors. The resulting interactions highlight the need for full examination of both factors, and may be the reason that previous efforts at examining decision-making in desktop VR have proved inconclusive. The results of Experiment 2 support previous findings that walking tends to improve performance in route learning, but the other levels of information are not so straightforward.

The interaction of information and decision-making was driven primarily by the Wheelchair groups, both of which showed somewhat surprising performance. The Wheelchair conditions were included to examine the contribution of vestibular information, beyond vision alone. Not only was the Free Wheelchair group worse than the Free Walking group, but the Guided Wheelchair group was also somewhat better (although not significantly so) than the Guided Video condition. A number of reasons

may be behind the poor performance in the Free Wheelchair group. First, the Free Wheelchair group was not significantly worse on measures of spatial ability. Although the Free Wheelchair group visited fewer objects during exploration, this aspect of exploration showed no correlation at all with performance. They also tended to turn their heads less during exploration, but this measure also did not correlate with performance. Overall, the Free groups explored significantly less evenly than the Guided groups, whose exploration paths were matched to the Free Walking group, suggesting that the Free Wheelchair group may have explored less evenly than the Free Walking group. Evenness of exploration was correlated with performance. It is uncertain whether unevenness of exploration was caused by being in the wheelchair, or whether this group was just not particularly good at exploring. However, the Free Video group also tended to show more uneven exploration than the Free Walking group, and performance in that condition was not nearly as poor as in the Free Wheelchair condition.

The Free Wheelchair group made discrete decisions, pressing the button only at choice points, while those in the Free Video condition made continuous responses by pressing the keys to continue movement. In addition, the discrete decisions may have been made slightly earlier than those in the Video condition, in order to provide time for the experimenter to turn the wheelchair. Most participants reported feeling that the use of the tablet PC was fairly natural and did not cause any difficulties. During practice, participants in the Free Wheelchair seemed as much at ease with the controller, if not more so, than participants in the Free Video. Finally, there was some aspect of communication involved, although care was taken to minimize this factor. Participants may have behaved differently since they were not in direct control of the wheelchair, or

may have thought of their exploration more in terms of left and right turns. Pilot participants in a motorized wheelchair that used a joystick to continuously control movement showed somewhat better performance than those in the Free Wheelchair condition, although there were also a number of participants who failed to find all of the objects in this pilot study. Together, these factors may have reduced performance in the Free Wheelchair group.

Interestingly, those in the Guided Wheelchair group did not appear to suffer from the effects of decision-making quite as much as those in the Guided Walking group. While the overall proportion correct in the Guided Wheelchair was lower than the Free Walking group, it was not significantly lower, and is not significantly different from the Guided Walking group or the Guided Video group. None of the individual difference measures suggest that the Guided Wheelchair group had any advantage over the other groups. Passively riding in a wheelchair may require less attention than the Guided Walking group, and the signal-to-noise of the vestibular input in a wheelchair may be higher than for walking. The addition of vestibular information for the Guided Wheelchair may have provided some advantage over the Guided Video group. Thus, there appears to be an interaction between decision-making and vestibular information that allowed the Guided Wheelchair group to learn the environment reasonably well. Overall, the Wheelchair conditions do not appear to be a valid test of the contribution of vestibular information and should be dropped from consideration.

In addition to the main experimental manipulations, the third main conclusion from Experiment 2 is that large sex differences appeared in all groups, where women tended to perform worse than men overall. Women also had lower scores on all of the

spatial abilities measures. It thus appears likely that the poorer performance was related to spatial abilities, and not some effect of the experimental procedures. Women did report higher ratings of nausea than men, especially in the wheelchair and video conditions. While experience of nausea was not correlated with performance, it is possible that it affected female's ability to learn the environment in these conditions. Women also had less video game experience, which may have contributed to the difference in performance between men and women. Previous research has found mixed results for sex differences in spatial navigation, with some determining that there are large sex differences (Moffat, Hampson, & Hatzipantelis, 1998; Waller, 2000; Wolbers & Hegarty, 2010). Others have found few differences or that primary differences are related to specific types of spatial tasks, although route learning tends to be one of the tasks with similar performance (Castelli, Corazzini, & Geminiani, 2008; Coluccia & Louse, 2004). The results of Experiment 2 suggest that women do have lower spatial abilities than men, which are reflected in the shortest route task performed here. However, spatial abilities may be susceptible to stereotype threat (Spencer, Steele, & Quinn, 1999), where membership of 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 vary depending on the level of stereotype threat or anxiety for spatial skills (Lawton & Kallai, 2002; Martins, Johns, Greenber, & Schimel, 2006; McGlone & Aronson, 2006). Given that the present experiment was not designed to investigate sex differences and the procedure did not take specific steps to alleviate potential stereotype threat, it is possible that this was a factor in the observed differences.

Finally, spanning the experimental manipulations, the large individual differences are striking. Even with full idiothetic information, and the ability to make decisions about exploration, some participants still performed quite poorly at the shortest route task. And even with while simply watching a video, some participants were still able to learn the layout of the maze quite well. These individual differences make it difficult to observe effects of the experimental manipulations. At the same time, the very presence of experimental effects despite these large individual differences is all the more compelling.

When examining the overall group, it appears that factors related to spatial abilities significantly contributed to performance on the shortest route task. Scores on self-reported sense of direction, perspective-taking, route following, and video game experience all were correlated with performance. Perspective-taking might contribute to graph learning by allowing navigators to learn the graph from different viewpoints, making it easier to traverse routes from different directions. However, only the two measures of evenness of exploration were correlated for the overall group, the Free Walking group, and the Guided Walking group. Compared with Experiment 1, the influence of spatial abilities is somewhat lower, and there were no correlations with spatial abilities in the Free Walking group, suggesting that spatial abilities plays a smaller role in the shortest route task. Notably, for most of these measures, the correlations appeared to be driven by people with low spatial abilities. That is, a very even exploration pattern might not necessarily help a person learn the graph structure, but a very uneven pattern was difficult to overcome. One note of caution must be taken about the individual difference measures: the spatial abilities tests were performed after the test

phase of the experiment, to prevent them from biasing the testing. However, it is possible that performance on the shortest route task could bias participants' responses in the spatial abilities assessments. Those measures related to experience in during exploration, however, are unlikely to have been affected by order or procedure.

It is likely that participants explore unevenly because they have poor spatial abilities. For example, in the Free Walking group, although it was not significantly correlated, the SBSOD self-report scale showed the next strongest relationship with proportion correct. These two measures were not correlated when looking at just the Free Walking group ($r_{30} = 0.248$, $p = 0.177$), but they were correlated when examining all of the three Free decision-making groups altogether ($r_{62} = 0.252$, $p = 0.045$). Thus, it appears that participants manifested their spatial abilities in this task by how they explore an environment. It is unclear whether particular spatial strategies assisted participants in creating more effective exploration patterns, or whether this factor is directly related to spatial ability.

Overall, Experiment 2 suggests that the ability to make decisions appears to play an important role in learning the graph structure of an environment, particularly when idiothetic information is available. This result is consistent with the hypothesis that making decisions contributes to linking paths and places in graph knowledge, but not survey knowledge. Surprisingly, idiothetic information seems necessary for decision-making to contribute to graph knowledge, implying that graph knowledge may not be purely topological, but incorporate some metric information. It remains an open question of just how decision-making aids spatial learning. It is possible, for example, that making decisions directs the navigators' attention to aspects of the environment that are

relevant to graph learning. Experiment 3 focuses on the role of attention in learning the graph of the environment.

Chapter 5

Experiment 3: The Contribution of Attention to the Acquisition of Graph Knowledge

Introduction

Experiment 1 addressed whether vestibular or idiothetic information and decision-making are effective components of “active” learning for survey knowledge; Experiment 2 addressed the same question for graph knowledge. The answer seems to be that idiothetic information and decision-making play somewhat different roles in “active” learning. Experiment 3 examines another possible component of active spatial learning: the deployment of attention.

Most previous work on spatial learning informed participants that they would be tested on their spatial knowledge or gave participants a task that might affect their attention, such as directing them to search for a particular item. Van Asselen et al. (2006) examined incidental route learning by instructing half of their participants to attend to their route for a later test, while the other half were simply told they had to move to another location in the building; they experienced the route without additional orienting information. Those who were told about the test were able to reverse their route better than those who were not told, although both groups were able to identify landmarks and put them in order. Similarly, Moeser (1988) found that people who worked in a hospital for two years still did not have full survey knowledge of the building, likely because most of their daily tasks involved following familiar routes rather than attending to distances and directions between locations in the building.

Distracting participants with simultaneous interference tasks also suggests that some aspects of route learning, such as the appropriate turns to take, require attention (Albert et al., 1999; Allen & Willenborg, 1998; Anooshian & Siebert, 1996; Garden et al., 2002; Meilinger et al., 2008). Yet distracted participants could often still identify

landmarks and knew the sequential order of the route. However, most of these experiments were performed while seated and watching a video of a route, removing possible contributions of idiothetic information to route learning. In addition, interference tasks that require cognitive resources may be different from simply failing to attend (and incidentally learn) the route.

Directing attention to specific aspects of the environment has proven somewhat fruitful in determining how attention contributes to spatial learning. Participants who were instructed to learn the sequence of the landmarks had greater route knowledge compared to those who learned the correct turn at each individual landmark, possibly due to increased attention to the temporal order of the route (Anooshian, 1996). Taylor et al. (1999) found that those who were instructed to learn routes through a building were better at route knowledge than those who were instructed to learn the building layout. Both groups performed equally well on tests of survey knowledge. Thus, the orienting task with which a navigator is charged may affect the quantity and quality of spatial knowledge acquired.

Thus, the literature suggests that attention facilitates the acquisition of route knowledge, whereas landmarks and possibly sequences appear to be learned incidentally. However, several questions remain unanswered. First, it is unclear whether the advantage of attending to one's route extends from route knowledge to graph or survey knowledge. Second, there is very little evidence about whether attending to the 2D spatial layout similarly affects the acquisition of graph and survey knowledge. Finally, it is unknown how individual differences in spatial ability are related to the allocation of attention, and whether they might be remedied by strategic deployment of attention.

Experiments 1 and 2 examined survey and graph learning of a new environment without any particular direction of attention during learning. The instructions in Experiments 1 and 2 were intentionally open-ended: “Find all the objects and learn their locations.” Participants were not informed about the type of spatial structure they should learn, the kind of test they would be performing, or even that they would be tested at all. Many participants reported that they were caught off-guard by the test, or that if they had known about the test they would have paid more attention or attended to different aspects of the maze. Although attention was not explicitly manipulated in Experiment 2, it could have mediated the effect of decision-making: making decisions might have directed attention to environmental properties relevant to graph knowledge, such as the left/right branching of paths or which path led to which object. Decision-making may have also allowed explorers to predict what they would encounter around each corner, which may increase attention. Experiment 3 probed the contribution of attention by informing participants that they would be tested on the locations of the objects and giving them an orienting task to direct their attention to relevant spatial properties. Because it is unclear exactly which environmental features will facilitate graph or survey knowledge, the best solution was to give participants instructions and practice on the shortest route or shortcut task. Performance in the shortest route test was compared to the Free Walking group in Experiment 2, which was not given an orienting task.

It is expected that the effects of attending to environmental properties on spatial knowledge will be task-specific. First, to the extent that attention to route properties facilitates the encoding of ordinal structure, it should contribute to graph knowledge and interfere with metric survey knowledge. However, if attention merely strengthens place-

action associations, it will enhance neither, but only contribute to route knowledge as previously reported. Second, conversely, to the extent that attention to 2D object locations facilitates the encoding of metric structure, it should contribute to metric survey knowledge, but not graph knowledge.

The results of Experiment 3 did not confirm these hypotheses. The results suggest that an orienting task did not make a significant contribution to graph knowledge in the shortest route test. Large individual differences were observed in all groups, and several measures were correlated with performance in the shortest route task.

Methods

Participants

Participants were recruited through advertisements and were paid for their time at the rate of \$10/hour. All participants signed forms indicating their informed consent to be a part of the study in fulfillment of the requirements of the Brown University IRB. 46 (24 female) people participated in the experiment. 9 (7 female) withdrew due to symptoms of simulator sickness, 1 (0 female) for failure to find all of the objects during exploration, and 4 (1 female) for technical problems. 32 participants (16 female) completed the experiment. Mean age of participants who completed the study was 22.97 (SD 5.04).

Equipment

Equipment was the same as in Experiments 1 and 2.

Environment

The maze environment was the same as in Experiments 1 and 2 (see Figure 1).

Design

The design of the experiment involved 2 groups of participants, in a between-subjects group design. One group received the Graph orienting task, and the other received the Survey orienting task; after learning, both groups were tested on their graph knowledge using the shortest route task. Performance in the shortest route test was compared to the Free Walking group ($n = 32$) in Experiment 2. Because this group received no additional orienting task, it will be referred to as the No Orient group. Each group of consisted of 16 participants.

Learning Phase

In the 10-minute learning phase, all participants walked with full idiothetic information and were free to make decisions about where they wanted to explore. All participants were instructed to “find all the objects and learn their locations.” They were then informed that they would be tested on the locations of the objects in the maze and received two practice trials on the orienting task. Participants in the Graph Orient group were informed that they would have to walk to the objects in the maze, using the hallways to get there. Participants in the Survey Orient group were informed that they would have to turn to face objects in the maze, as if they were looking through the walls of the maze at the object. The instructions for these orienting tasks did not inform participants which aspects of the environment would aid them in learning the graph or survey structure, but instead the assumption was that navigators would attend to the appropriate properties if they know what the test task will be.

Test Phase

In the test phase, all participants performed the shortest route task as in Experiment 2. Participants started at one object and were instructed to follow the corridors of the maze to reach the target object location, taking the shortest route possible within 30 seconds. Occasional detour trials were included in the test phase. This task probed graph knowledge because participants had to form novel routes between objects that were not necessarily directly traveled during exploration.

The dependent measures and analyses were the same as in Experiment 2.

As in Experiment 2, 8 pairs of objects were used, with 5 trials per object pair, for a total of 40 trials. All trials were presented in a random order with the exception that trial types did not repeat back-to-back.

Procedure

Procedures were the same as Experiments 1 and 2 except for the addition of an orienting task during the learning phase. After receiving practice with a maze environment, where they were given one practice trial with the task in the experiment, the learning phase began. The Graph Orient group was asked to walk to one of the objects in the practice maze. The Survey Orient group was asked to turn and face one of the objects in the maze, as if they were looking through the maze walls at the object. Participants then had 10 minutes of exploration. After 4 minutes of exploration, participants were given 2 practice trials with the orienting task in the test environment, again either going to one of the objects in the maze or turning to face one of the objects. Participants in the Graph Orient group were given 30 seconds to find the target object. If they did not find the object during that time, the experiment moved on to the next trial or, if it was the second trial, they were told to continue exploring. The time taken during these trials

counted toward the 10-minute learning phase, since participants were able to learn more about the maze during these practice trials.

Participants in the Survey Orient group were instructed to tell the experimenter when they thought they were facing the target object, and then the experimenter clicked the mouse to move to the next trial. The time taken for these practice trials did not count toward the 10-minute learning phase, since participants were not moving and could not learn more about the maze during the practice. After those two practice orienting trials, the participants were allowed to explore freely for the remainder of the 10 minutes. After the 10-minute exploration, participants were then given 2 practice trials with the shortest route test, followed by 40 experimental trials.

Results

Proportion Correct

Analysis of the proportion of correct trials was conducted using a 3x2 (orienting task x sex) unequal-n ANOVA. The ANOVA found no effects of orienting task ($F_{2,61} = 0.521$, $p = 0.597$, $\eta_p^2 = 0.018$) or sex ($F_{1,62} = 0.280$, $p = 0.599$, $\eta_p^2 = 0.005$), and no interactions ($F_{2,58} = 0.826$, $p = 0.443$, $\eta_p^2 = 0.028$). While the Survey Orient group had the highest proportion correct of any of the groups, this difference was not significant. These results suggest that additional orienting tasks did not affect performance in the shortest route test (Figure 22).

Individual performance is shown in Figure 23. Participants are shown in rank order of proportion correct, with lowest performing participants on the left and most accurate participants on the right. Because there were twice as many participants in the No Orient group as the other two groups, this group is depicted at twice the density, such

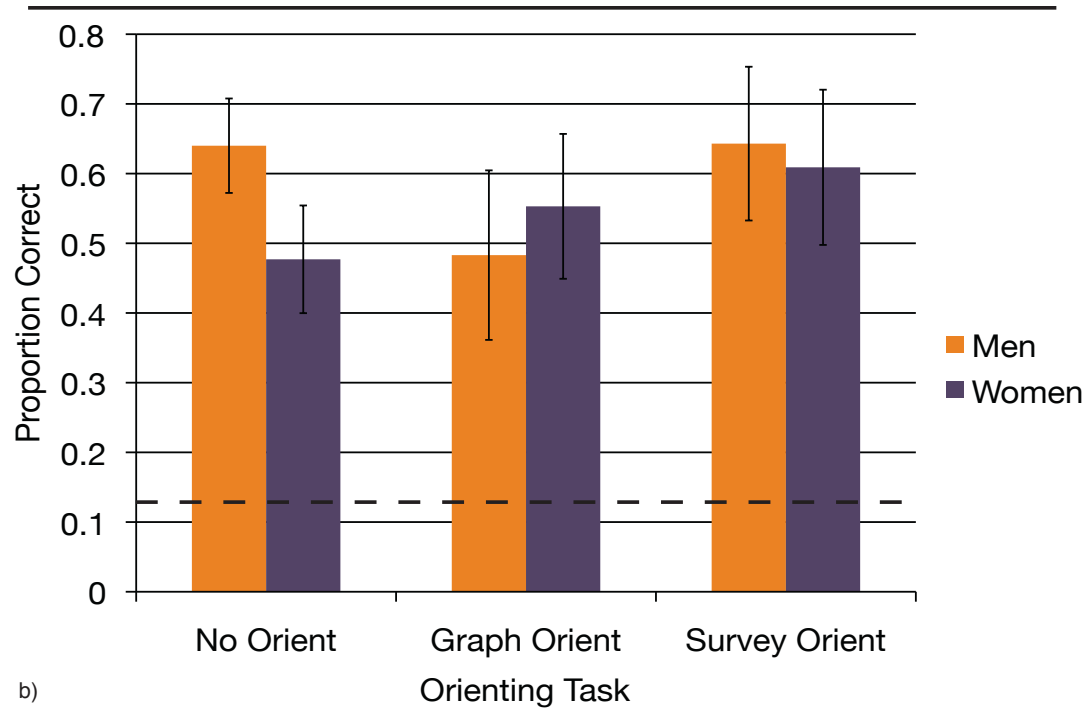
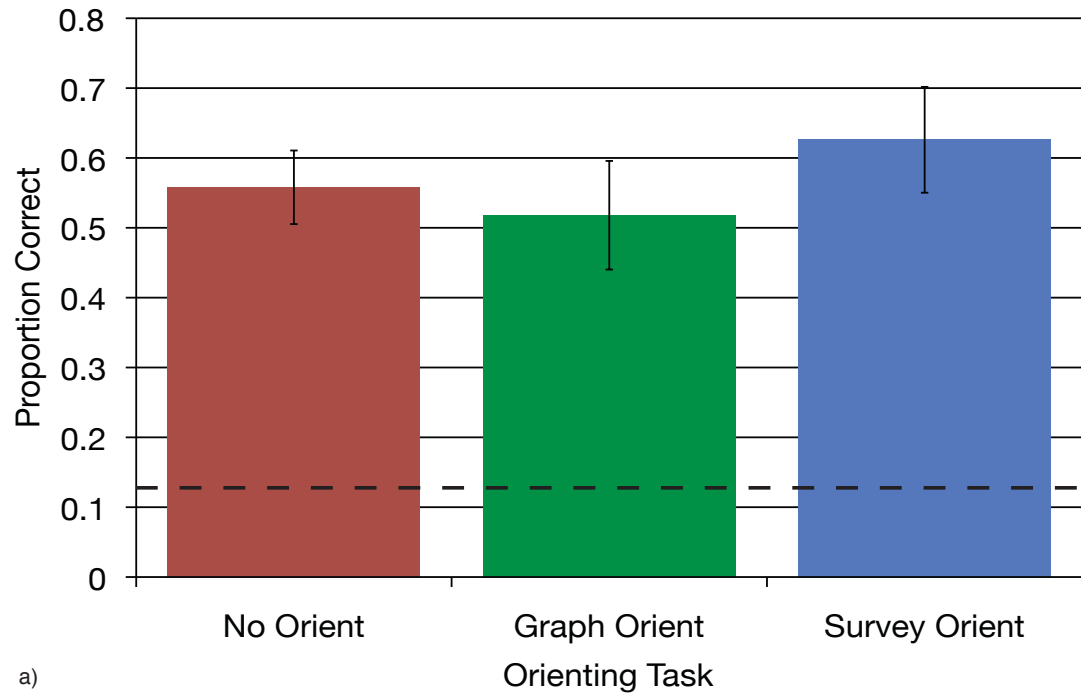


Figure 22. Proportion of trials ended at the correct target object location the three orienting task conditions. Dashed line indicates chance level. N = 64. a) Proportion correct of the three experimental groups. b) Proportion correct of the three experimental groups separated by sex.

that the overall scales are matched between the groups. Qualitative assessment of this figure suggests that the orienting tasks did not aid graph learning at the low ends of either of the orienting groups, since there were still about the same number of participants performing near chance as in the No Orient group. The only notable difference between the groups is in the third quartile, where the Survey Orient group appears to perform somewhat better than the No Orient and Graph Orient groups, suggesting a small boost of graph knowledge for those attending to the object locations. However, because this was a fairly small proportion of participants overall, the groups did not differ significantly.

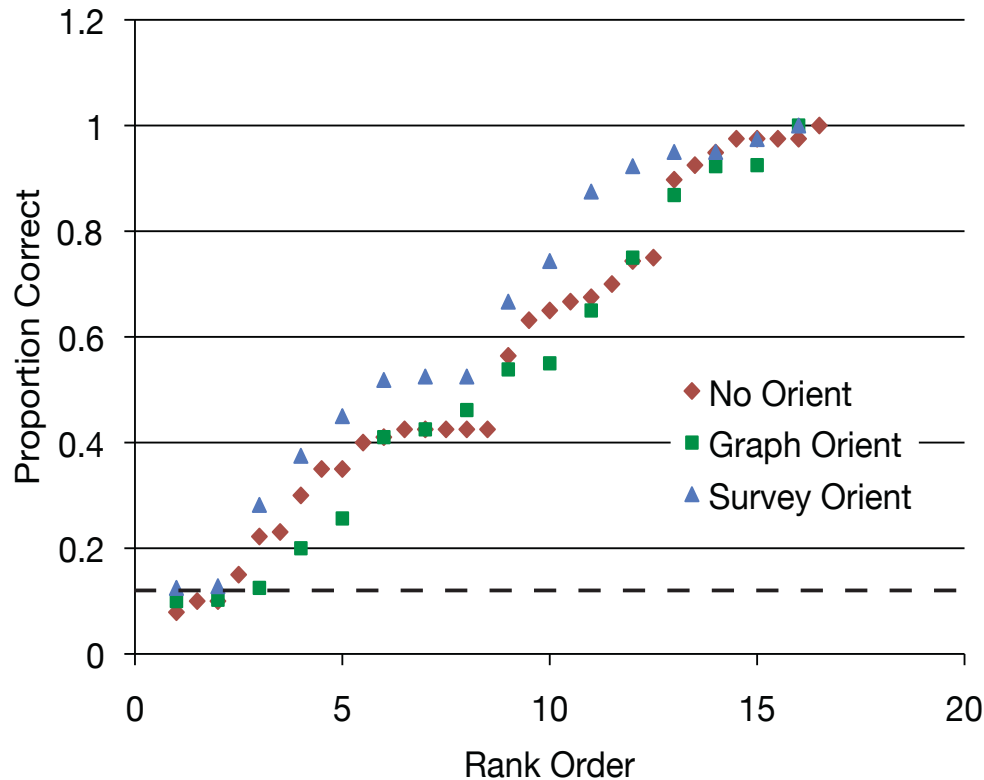


Figure 23. Individual performance in the three orienting task conditions. Participants in each group were ordered from least proportion correct to great proportion correct. Because there were more participants in the No Orient group, they were ranked at twice the density, so that the scales corresponded between the groups. Dashed line indicates chance level, 0.125.

Path length

A 3x2 (orienting task x sex) unequal-n ANOVA found a significant main effect of

orienting task on the length of the path taken during the test trials ($F_{2,61} = 7.529$, $p = 0.001$, $\eta_p^2 = 0.206$). There were no effects of sex ($F_{1,62} = 1.207$, $p = 0.276$, $\eta_p^2 = 0.020$) and no interactions ($F_{2,58} = 0.383$, $p = 0.684$, $\eta_p^2 = 0.013$). Post-hoc Tukey tests showed that those in the Graph Orient group took significantly longer paths than in the No Orient group ($p = 0.001$). These results suggest that while the experimental groups found the target object equally often, the Graph Orient group took the least efficient routes to the target (Figure 24). This result implies that attending to the graph structure may interfere with learning metric information about distances. There was also a significant effect of sex on the standard deviation of path length ($F_{1,62} = 6.290$, $p = 0.015$, $\eta_p^2 = 0.098$), with women having a higher standard deviation of path length than men.

Travel Time

There was a significant effect of sex on the standard deviation of travel time ($F_{1,62} = 4.794$, $p = 0.033$, $\eta_p^2 = 0.076$), with women having a higher standard deviation than men. There were no significant effects on the mean of travel time.

Additional Measures

There were no significant effects for consistency, distance from target, the number of trials where time limit expired, sketch map scores, detour trials, or learning during the testing.

Trial Types

Individual trial types were examined in an item analysis. A repeated-measures ANOVA was conducted with item as a within-subject factor and orienting task and sex as between-subjects factors. This analysis found a significant item effect ($F_{7,57} = 7.270$, $p < 0.001$, $\eta_p^2 = 0.111$). Post-hoc Tukey tests found that participants were correct on the trial

starting at the bookcase and ending at the well (72.8%) significantly more than four other trial types, although other comparisons were not significant.

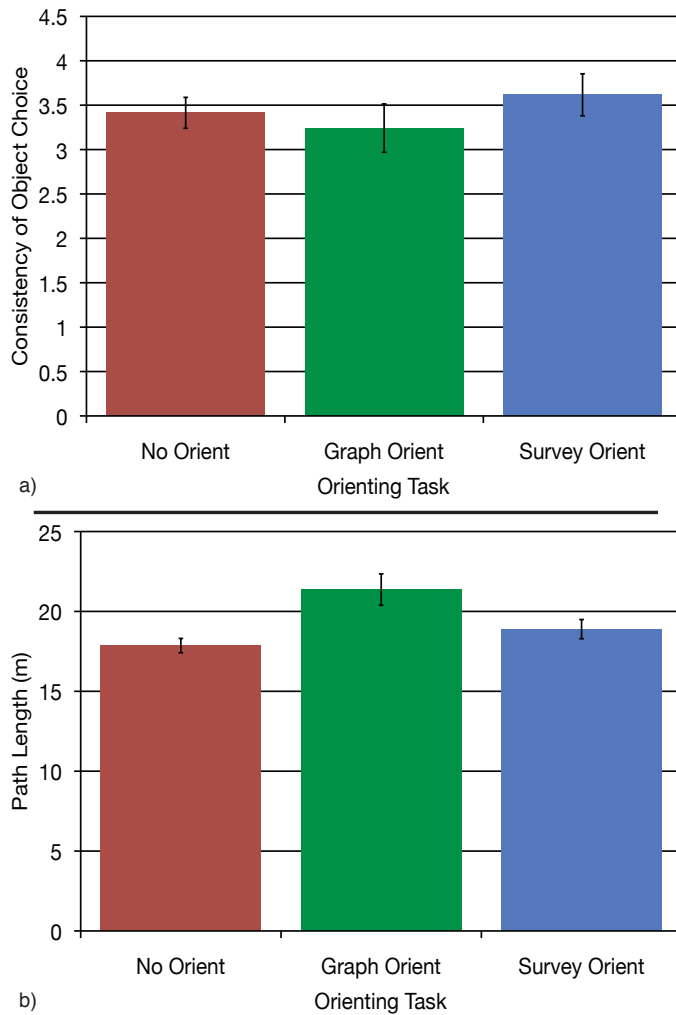


Figure 24. Additional results from Experiment 3, N = 64. a) Consistency of object choice. b) Path length during the test trials.

Individual Differences

The large individual differences highlighted in Figure 16 and Figure 23 warrant further consideration. First, it must be established that the groups did not differ on measures of spatial ability that might affect the outcome of the experimental manipulations. Second, it is of interest to determine what spatial measures correlate with performance on this graph task.

The measures were the same as those used in Experiments 1 and 2.

Group comparisons. The first analysis was aimed at determining whether the random assignment of participants resulted in one group having higher spatial abilities than the others. 2-way ANOVAs (orienting task x sex) were performed on the 7 measures of spatial abilities and experience.

Participants were generally the same age. There was a marginal difference in age between men and women ($F = 3.534$, $p = 0.065$, $\eta_p^2 = 0.057$), with men being somewhat older than women.

The three tests of spatial abilities found few differences between the experimental groups. The SBSOD self-report sense of direction showed a marginal difference between the three experimental groups ($F = 2.536$, $p = 0.088$, $\eta_p^2 = 0.080$), with the No Orient group reporting the best sense of direction and the Graph Orient group reporting the worst sense of direction. A Tukey post-hoc test found a marginal difference between those two groups ($p = 0.072$). There were no differences between the groups on the PTSOT. For the Road Map Test, there was a marginal orienting task x sex interaction ($F = 2.849$, $p = 0.066$, $\eta_p^2 = 0.091$). Men in the Survey Orient group had the highest Road Map scores, while men in the Graph Orient group had the lowest. Women in the No Orient group also had fairly low Road Map scores.

The three video game measures showed primarily sex differences. For current video game use, there was a significant orienting task x sex interaction ($F = 3.967$, $p = 0.024$, $\eta_p^2 = 0.120$). Women in the Graph Orient group played the most video games, while in the other two groups men played more video games than women. There were no

group differences for current navigational video game use, but men did play more navigational video games than women in the past ($F = 9.698$, $p = 0.003$, $\eta_p^2 = 0.143$).

In sum, there were few differences in spatial abilities and experiences between the groups in Experiment 3. The primary difference was that men generally had more experience with video games than women. Video game experience often involves learning the layout of a complex environment, and more experience with video games could assist in learning the graph structure of the environment, yet there was no overall sex difference in the shortest route test.

Differences in VR experience. Analysis of differences in VR experience provides a way of examining whether the three orienting groups differed in their exposure to the maze or their subjective experiences. 2-way ANOVAs (orienting task x sex) were performed on the 7 measures of VR experience.

There were no differences between the groups for ratings of nausea or immersion.

For the total distance traveled during the learning phase, there was a significant difference between the three experimental groups ($F = 7.671$, $p = 0.001$, $\eta_p^2 = 0.209$) and a significant orienting task x sex interaction ($F = 3.803$, $p = 0.028$, $\eta_p^2 = 0.116$). Post-hoc Tukey tests found that the No Orient group traveled significantly less than the Graph Orient group ($p = 0.001$) and marginally less than the Survey Orient group ($p = 0.055$), although men in the Survey Orient group did not walk as far as women in that group. There was also a significant difference between the groups for the total angular rotation ($F = 4.873$, $p = 0.011$, $\eta_p^2 = 0.144$). Post-hoc Tukey tests found that the No Orient group had significantly less head rotation than those in the Survey Orient group ($p = 0.025$) and marginally less than the Graph Orient group ($p = 0.051$). The practice trials were

included in the angular rotation analysis, and some of the angular rotations in the Survey Orient group were made during the practice trials, when they had to face a target object. However, these rotations were generally less than one full turn (360 degrees), and so were unlikely to be the primary contributor to differences in angular rotation. It is possible that participants in the Graph and Survey Orient groups traveled further and rotated more during the learning phase because they were continuing to explore the maze, to look around at each corner, or to test their own knowledge of the maze by standing in place and rotating to point to objects. In contrast, those in the No Orient group may not have been as motivated to thoroughly explore the maze during the entire learning phase, either by not walking as much or by not looking down all the hallways and alcoves.

There were no differences between the groups for the two measures of evenness of exploration during the learning phase.

In sum, while the groups did not differ in nausea or immersion, the analysis of differences in VR experience suggests that the different orienting groups did explore somewhat differently. The No Orient group did not walk as far or have as much total angular rotation as the two groups with orienting tasks. It is unclear whether the orienting task led participants to explore more of the environment, or if participants in those groups just walked faster. Although the two orienting groups showed somewhat different patterns of exploration, suggesting that they were attempting to encode the environment differently from those in the No Orient group, this alteration in encoding did not appear to facilitate learning the graph structure of the maze. On the other hand, participants in all groups tended to visit the objects equally evenly, and about the same

number of times, so these factors were unlikely to contribute to differences in the shortest route test.

Correlations with performance. As in Experiments 1 and 2, correlations between spatial ability measures and proportion correct in the experimental task were analyzed, using two approaches. The first approach combined performance over all 64 participants from the three experimental groups, providing large statistical power. The second approach examined the Graph Orient and Survey Orient groups individually (the No Orient group was examined in Experiment 2).

	r	p-value	df
Age	-0.018	0.886	62
SBSOD	-0.182	0.150	62
PTSOT	-0.413	0.001**	61
Road Map Test	0.251	0.047*	61
Current Video Game Use	0.209	0.098	62
Current Navigational Games	0.074	0.559	62
Past Navigational Games	0.071	0.575	62
Nausea	-0.066	0.606	62
Immersion	0.052	0.681	62
Distance Traveled during Exploration	-0.152	0.230	62
Total Angular Rotation during Exploration	0.085	0.503	62
Mean Number of Objects Visited during Exploration	-0.108	0.394	62
StDev of Objects Visited during Exploration	-0.402	0.001**	62
Range of Objects Visited during Exploration	-0.433	<0.001***	62

Table 9. Correlation coefficients for individual difference measures and proportion correct in the shortest route test, combined over all 64 participants in Experiment 3.

Results of the overall correlations are listed in Table 9 and Figure 25. Two of the spatial abilities tests showed significant correlations with performance in the shortest route task. Perspective-taking ability as measured by PTSOT errors was correlated with proportion correct ($r_{61} = -0.413$, $p = 0.001$). The Road Map Test was also correlated with performance ($r_{61} = 0.251$, $p = 0.047$). The standard deviation of the number of objects visited during the learning phase ($r_{62} = -0.402$, $p = 0.001$) and the range of objects visited

during exploration ($r_{62} = -0.433$, $p < 0.001$) were both correlated with proportion correct in the shortest route test.

Examination of the Figure 24 suggests that the correlations were fairly equally distributed. PTSOT errors and range of object visits in the learning phase appear to be driven primarily by those with the worst spatial abilities, such that low error in the PTSOT might not necessarily predict performance on the graph task, but those with very high errors were unlikely to do well.

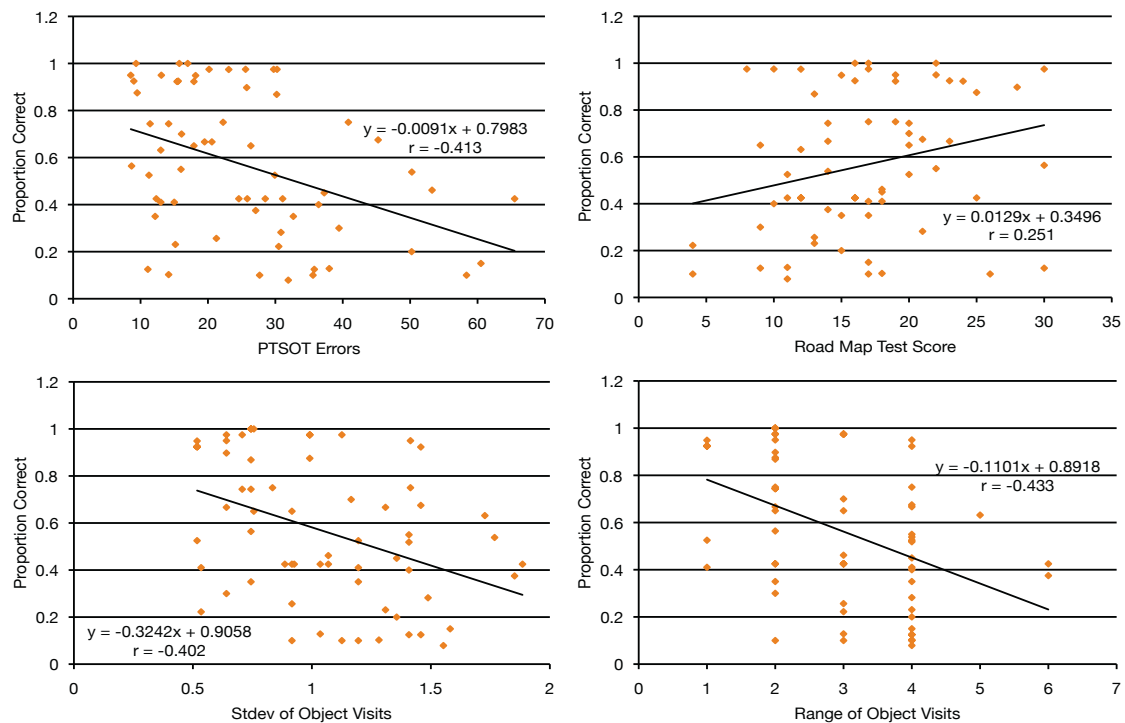


Figure 25. Significant correlations between 6 individual difference measures and proportion correct for all participants in all groups. Each data point represents the mean score for one participant. Correlations are for PTSOT errors, Road Map Test scores, the standard deviation of the number of object visits during exploration, and the range of object visits during exploration.

The Graph and Survey Orient groups were also tested (Tables 10 and 11 and Figure 26). As reported in Experiment 2, only the two measures related to evenness of exploration were significantly correlated in the No Orient group. In the Graph Orient group, nausea ratings ($r_{14} = -0.504$, $p = 0.046$), PTSOT error ($r_{14} = -0.498$, $p = 0.049$), and

Road Map Test scores ($r_{14} = 0.511$, $p = 0.043$) correlated significantly. Those who experienced more nausea had worse performance, and those with better spatial abilities had better performance. Interestingly, the measures of evenness were not correlated with performance. In the Survey Orient group, PTSOT errors ($r_{13} = -0.539$, $p = 0.038$) and the standard deviation of the number of object visits ($r_{14} = -0.518$, $p = 0.040$) were correlated with performance, with the range of object visits marginally correlated ($r_{14} = -0.497$, $p = 0.050$). Those with even exploration and lower PTSOT errors performed better on the shortest route test.

	r	p-value	df
Age	0.126	0.641	14
SBSOD	0.223	0.405	14
PTSOT	-0.498	0.049*	14
Road Map Test	0.511	0.043*	14
Current Video Game Use	0.131	0.629	14
Current Navigational Games	0.277	0.299	14
Past Navigational Games	0.062	0.819	14
Nausea	-0.504	0.046*	14
Immersion	-0.211	0.412	14
Distance Traveled during Exploration	-0.147	0.587	14
Total Angular Rotation during Exploration	0.197	0.465	14
Mean Number of Objects Visited during Exploration	-0.243	0.364	14
StDev of Objects Visited during Exploration	-0.391	0.134	14
Range of Objects Visited during Exploration	-0.435	0.092	14

Table 10. Correlation coefficients for individual difference measures and proportion correct in the shortest route test, for the 16 participants in the Graph Orient group in Experiment 3.

Examination of Figure 26 shows that all of the significantly correlated spatial ability measures were fairly evenly distributed among the participants, such that the correlations do not appear to be driven by those at the top or bottom end of the spectrum. Interestingly, the Graph Orient group is the first incidence of nausea ratings being correlated with performance. This group also had more head rotation during the learning phase than the other groups, possibly explaining this finding. No one measure was

significantly correlated in all three orienting tasks. The PTSOT was correlated in the Graph and Survey Orient groups, but not in the No Orient group. The standard deviation of the number of object visits was correlated in the No Orient group and the Survey Orient group, but not in the Graph Orient group. However, many of these measures overlapped between groups and with the overall analysis, such that PTSOT errors, Road Map Test scores, and the standard deviation of object visits during the learning phase appear to be most strongly related to graph learning under conditions of full idiothetic information during the learning phase.

	r	p-value	df
Age	0.290	0.276	14
SBSOD	-0.306	0.250	14
PTSOT	-0.539	0.038*	13
Road Map Test	0.028	0.921	13
Current Video Game Use	0.409	0.116	14
Current Navigational Games	0.247	0.357	14
Past Navigational Games	-0.367	0.162	14
Nausea	-0.361	0.170	14
Immersion	0.358	0.174	14
Distance Traveled during Exploration	-0.140	0.604	14
Total Angular Rotation during Exploration	-0.001	0.997	14
Mean Number of Objects Visited during Exploration	0.046	0.867	14
StDev of Objects Visited during Exploration	-0.518	0.040*	14
Range of Objects Visited during Exploration	-0.497	0.050	14

Table 11. Correlation coefficients for individual difference measures and proportion correct in the shortest route test, for the 16 participants in the Survey Orient group in Experiment 3.

Discussion

Experiment 3 examined the role of attention in the acquisition of graph knowledge. The results of Experiment 3 suggest that, first, the orienting task had no effect on graph learning, and second, for the first time there was minimal sex difference. One group of participants was given an orienting task designed to facilitate graph learning, while another group was given an orienting task designed to facilitate survey

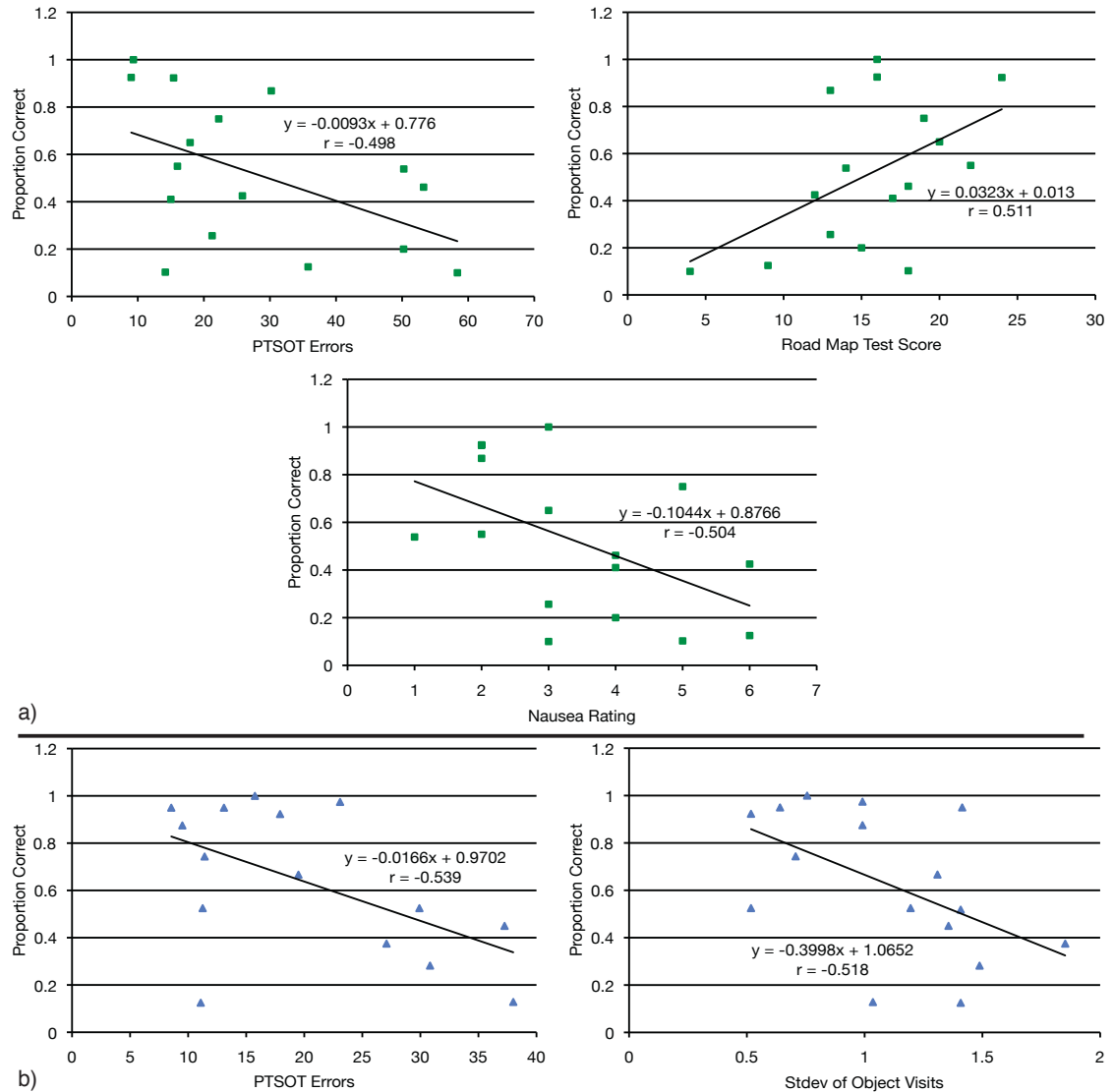


Figure 26. Significant correlations between individual difference measures and proportion correct for the shortest route test. Each data point represents the mean score for one participant. a) Correlations for the Graph Orient group. Correlations are for PTSOT errors, score on the Road Map Test, and nausea ratings. b) Correlations for the Survey Orient group. Correlations are for PTSOT errors and the standard deviation of the number of object visits during exploration.

learning. These groups were compared to a group that received no orienting task during the learning phase. All participants were tested on the shortest route task, an assessment of graph knowledge. Surprisingly, there were no significant differences between the three orienting tasks in the proportion of correct trials. For the first time, there were also no major differences between men and women on the shortest route test.

The only significant effect of orienting task observed in this experiment was that participants in the Graph Orient group took longer paths during the test phase. This result indicates that this group did not learn the graph structure of the environment as well as the other groups, suggesting that the orienting task actually hindered their learning. However, this group did reach the correct target object as often as the other groups, so even without taking the most efficient paths, this group was still able to perform the task successfully. One possible explanation might be that participants learned associations between the object locations and landmarks (paintings) in the hallways, but did not always know the shortest way to get there. These participants may have simply walked until they found the appropriate painting, without full knowledge of the graph structure of the maze.

The lack of an effect of the orienting tasks is somewhat surprising. One possible explanation might be that given the task demands, the No Orient group suspected that they would be tested on their knowledge of the maze, making their acquisition of spatial knowledge during the learning phase intentional rather than incidental. While a number of participants in the No Orient group expressed surprise at the shortest route test, other participants may have anticipated some sort of test. Another possible explanation might be that participants attended to aspects of the environment during the learning phase that did not help them in the shortest route test. For example, some participants in the Graph Orient group reported memorizing where objects were located in relation to other objects; this strategy was difficult to implement during the test phase since the objects were replaced by red blocks. Participants were not informed that the objects would not be visible or that learning the connectivity of the paths and the landmarks in the hallways

was likely to be helpful. Another possibility is that making active decisions about exploration already maximizes any effects of attention, such that participants were already at their individual ceiling even without an orienting task. Thus, the addition of Graph or Survey orienting tasks might not facilitate any additional learning of the graph structure. It remains an open question whether the addition of an orienting task without decision-making or full idiothetic information, would aid graph learning.

The results of Experiment 3 are somewhat contrary to those of previous research. Van Asselen et al. (2006) found a significant advantage in route learning for participants who were told about the upcoming test compared to those who were not informed. The present experiment differs from theirs in that this experiment tested a more complex form of spatial knowledge, graph knowledge. Van Asselen et al. also gave the participants in the incidental group a cover story about moving to a new location, while participants in Experiment 3 did not receive any alternative information. The test and task demands may have been different enough between these two experiments that attention significantly contributed in one and not the other.

Taylor et al. (Experiment 1, 1999) found that participants instructed to learn routes had better route knowledge than those who were instructed to learn survey information. The results of Experiment 3 do not agree with those findings. If anything, the Survey Orient group had shorter paths than the Route Orient group on the shortest route test. Participants in Taylor et al. were given general instructions to learn route information, but were not given any practice with any of the tasks in the experiment. During the test phase, participants did not actually walk on routes between locations in the environment, instead they described routes and estimated the lengths of routes. These

methodological differences might account for the discrepant results in these two experiments.

In the second experiment by Taylor et al. (1999), participants were instructed to learn the shortest routes between specific locations as a route learning goal, or to learn the adjacencies of specific rooms to spur survey knowledge. In that experiment, participants with survey instructions were better at knowing some specific survey knowledge, such as which rooms were connected, but did not have an advantage for straight-line distances between locations or for general configurational knowledge. There were no differences between spatial learning goals in their tests of route knowledge. These results suggest that learning specific routes does not assist in acquiring the larger graph structure of the environment, and that learning specific adjacencies may not generalize to broader survey knowledge.

Anooshian (1996) found that participants who learned the sequence of the landmarks in a route had greater route knowledge compared to those who learned the correct left or right turn at each individual landmark. This finding suggests that attention to the larger structure and temporal order of the route may lead to greater route learning than attention to specific place-action associations. It is possible that the participants in the Graph and Survey Orient groups attended more to some of the specific associations between objects during the learning phase, which proved unhelpful during the test when the objects were no longer present. However, this result also might suggest that the Survey Orient group should have performed better, since they likely attended to the overall structure of the maze, but they were no better than the No Orient group. It is difficult to assess whether the results from a pure route test apply here, because

participants in Experiment 3 had to integrate together many different parts of the maze to perform the shortest route test successfully.

The results of Experiment 3 are not consistent with the hypothesis that the effect of attention to spatial properties is task-specific. There were few reliable differences between any of the three orienting tasks. In the face of this literature, the most conservative conclusion overall is that the orienting tasks were insufficiently strong to affect the acquisition of graph knowledge.

The other notable result from Experiment 3 is the lack of sex differences in the shortest route task. In Experiment 2, a main effect of sex was observed, with men performing much better than women; although the No Orient group did not have a significant sex difference ($F = 2.507$, $p = 0.124$, $\eta_p^2 = 0.077$), it showed the same trend. But Experiment 3 found no overall effect of sex, indicating that the two Orienting groups did not contribute to a sex difference, and men and women performed quite similarly in both of those groups.

It is possible that the active attention to properties of the environment helped women learn the graph structure as well as men. Bosco et al. (2004) found that visual-spatial working memory tasks that required active manipulation of spatial information contributed to women's spatial orientation more than men's. The orienting tasks may have evoked some active manipulation of spatial information that assisted women, and could account for the lack of sex differences in this experiment. However, it is important to note there were no sex differences in spatial abilities in these groups, whereas there were such differences in Experiment 2. Women in the Graph Orient group also played more video games than other groups, which may have contributed to their success. As

noted earlier, it is also possible that performance in the shortest route test could bias responses in the spatial abilities questionnaires and tests, since they were conducted after the test phase of the experiment. It is thus unclear whether the lack of sex differences in Experiment 3 was due to the orienting tasks during the learning phase or if the lack of differences in spatial abilities was responsible.

Finally, large individual differences in performance in the shortest route test were observed, similar to those seen in Experiments 1 and 2. The groups in Experiment 3 showed few differences. During the learning phase, participants in the Graph and Survey Orient groups tended to walk farther distances and turn their heads more, which may have given them more experience in the maze. However, all groups generally visited the same number of objects, and neither head rotations nor distance traveled during the learning phase were correlated with performance in the shortest route task.

Correlations with performance revealed that PTSOT errors, Road Map Test scores, and evenness of exploration were the primary factors related to performance in the shortest route test. These factors may be important to taking different perspectives. An even pattern of exploration suggests that the navigator was aware of where they had explored and where they had not, which may also require some ability to change perspectives to update their position within the maze. These factors may be important both during the learning phase and during the test phase of the experiment. Knowing what areas have been explored might also assist when searching for the target object, so that the explorer does not repeat travel through hallways unnecessarily.

Compared to the overall correlations in Experiment 2, age, SBSOD score, video game use, and immersion rating were no longer correlated with performance. It is

possible that some factors were especially important for some levels of information. For example, video game use might have been particularly important for those in the Video conditions, but might not be as relevant for those who walked during the learning phase. It is somewhat surprising that the self-reported sense of direction did not correlate with the three groups in Experiment 3. It seems that sense of direction might most closely relate to the types of learning important for graph knowledge, such as the connections between locations. However, it may be that a self-report measure is simply not sensitive to graph learning, or that the SBSOD is more important when navigating in circumstances without full idiothetic information.

The results from Experiment 3 suggest three possible conclusions. First, as described earlier, one possibility is that the orienting task manipulation was not strong enough to create an effect, or that participants learned the wrong relations during the learning phase. Given the previous literature, it seems that participants would be able to attend to the relevant properties during the learning phase. Second, another possibility is that attention does not contribute to graph learning beyond the effects of idiothetic information and decision-making. This conclusion seems plausible, but has not been tested. A final possibility is that attention actually is not a component of active learning for graph knowledge. It is conceivable that attention only strengthens the place-action associations in route knowledge, and does not aid in graph learning.

In sum, the results of Experiment 3 suggest that orienting tasks that direct attention to routes through the environment do not contribute to graph knowledge, at least when combined with full idiothetic information and free decision-making. The results of Experiment 2 suggested that cognitive decision-making constitutes an active component

of graph learning, but attention to different aspects of the environment does not seem to make a contribution over and above that factor.

Chapter 6: General Discussion

The series of experiments presented in this dissertation explored the contributions of active and passive exploration in spatial learning. While previous studies have often confounded the notions of active and passive by combining several different meanings of “active” under the same umbrella term, these experiments tested several different possible components of active learning separately. In addition to independently manipulating the components of active learning, these experiments tested how they contributed to learning two different types of spatial knowledge: survey and graph knowledge.

Active Learning of Survey and Graph Knowledge

The first two experiments manipulated visual, vestibular, and proprioceptive information, as well as the ability to make decisions during the learning phase. The results revealed strikingly different patterns of spatial learning for graph and survey knowledge. In Experiment 1, idiothetic information made a significant contribution to survey learning, such that walking during exploration led to lower errors and greater consistency than being wheeled in a wheelchair or watching a video. Making decisions during exploration played almost no role in survey learning. In contrast, Experiment 2 showed that decision-making made a significant contribution to graph learning. Participants who walked and made decisions during exploration had a greater proportion of correct trials than those who were guided along the same paths. The contribution of decision-making was most evident with full idiothetic information, suggesting that graph knowledge may incorporate some metric information.

The contrasting results in these two experiments suggest that components of active navigation affect different types of spatial knowledge in different ways. For

example, a participant in the Free Video condition may have learned the graph structure of the maze and thus knew that to get to the sink from the gear they needed to make two left turns and walk until they saw the red painting. But it did not help them learn the exact distances and angles between those two locations. Without proprioceptive and vestibular information, that explorer in the Free Video condition did not improve their ability to make a direct shortcut to the target. A navigator with only graph knowledge may be able to reach the target location, within the paths of the maze, without understanding where that metric location is in relation to the start position or the larger environment.

On the other hand, decision-making did not contribute to survey learning in Experiment 1. It is possible that decision-making did not significantly contribute to survey knowledge because it facilitates learning connections between locations, not the metric information about the environment. Decision-making might facilitate survey learning only if a navigator decided to take a direct path between the target object locations during exploration, giving them the opportunity to perform path integration over that portion of the maze. Decision-making may also be more likely to rely on verbal mediation of information, so that an explorer may say to themselves, for example, “Turn left, now here’s the well, and across from that should be the rabbit. Now if I go down the hall and turn right I should see the bookcase.” This process seems more likely to facilitate graph learning than survey learning because this type of verbal mediation relates to the connections between locations, not distances or angles.

The differences between graph and survey learning described here appear to be based on different learning mechanisms. Decision-making may contribute to graph knowledge by focusing on the connections between locations and allowing the explorer

to make predictions about the maze with every turn. They receive feedback about those predictions during the learning phase, which could drive reinforcement learning. In contrast, metric survey knowledge requires information about distances and angles, which are not available in a pure graph. Path integration processes can provide that metric information. Idiothetic information has been shown to contribute to path integration beyond the contribution of visual information alone (Kearns, 2003; Tcheang et al., 2011), which could be the reason that idiothetic information contributes to survey knowledge but seems to contribute much less to graph knowledge. It should be noted that the different learning mechanisms are likely due to the difference between these types of spatial knowledge themselves. Graph and survey knowledge have different amounts and forms of information. For example, complete survey knowledge contains graph information, but pure graph knowledge does not contain metric survey information. Thus, in order to obtain metric survey information, a different or additional learning mechanism is required than when obtaining graph information.

While many differences in performance were observed in performance between the shortcut test and the shortest route test, in many ways it is difficult to compare these two tests. The two tests were quite different, and had separate dependent variables that cannot be directly compared. Notably, the shortcut test in Experiment 1 removed the maze, objects, and painting during the test phase. If survey knowledge relies on contextual information, then removing the maze could diminish performance on the shortcut test. A possible contextual link may be one reason for the fairly poor performance in the shortcut task. Furthermore, the maze and paintings were present during the shortest route test in Experiment 2, although the objects themselves were not.

Having this additional context might explain why overall performance was much better in Experiment 2. In many ways, the shortcut test was a recall test, where participants had to know where the target object was located and how to best reach that target object without any additional cues during the testing procedure. In contrast, the shortest route test was closer to a recognition test. While participants did not actually see the correct object during the test phase, they could possibly recognize the nearby paintings, the connections of the hallways, or the shape of the object alcove. These divergent testing conditions in the shortcut and shortest route tests could explain the differences in performance observed in these two tasks. It seems unlikely, however, that these difference in test procedure would change the general pattern of results. A survey recognition test might improve performance overall, but it does not seem likely that it would alter the relative performance of the experimental groups, although this situation has yet to be studied in depth.

Despite these differences in test task, the main findings from these experiments support the hypotheses that idiothetic information contributes to survey learning and decision-making contributes to graph learning. Idiothetic information made the largest contribution to survey knowledge, as reflected in the shortcut test, while decision-making was the most reliable contributor to graph knowledge, as reflected in the shortest route task. If different components of active navigation influence these two types of spatial knowledge, it may indicate that they can be learned independently. Siegel & White (1975) proposed that landmark information is learned first, followed by route knowledge, and finally metric survey knowledge. With enough experience, survey knowledge is always acquired. However, recent evidence suggests that this ordering may not always

hold (e.g. Ishikawa & Montello, 2006), since some people acquire survey knowledge simultaneously with route information, and some people never acquire survey knowledge despite repeated exposure to the environment. In this dissertation, participants were only tested on one of the tasks, and so a direct comparison between an individual's graph and survey knowledge could not be made. It remains an open question whether participants who had accurate survey knowledge also had accurate graph knowledge, and vice versa. However, more participants were above chance in the shortest route task than in the shortcut test, suggesting that graph structure is somewhat simpler to acquire than metric survey knowledge, which is consistent with Siegel & White (1975). These results are also consistent with a single knowledge structure such as a labeled graph, with idiothetic information contributing to the metric labels and decision-making contributing to the path connectivity. It is also important to note that visual information alone is actually sufficient to extract much of the graph structure, since the Guided Video group was well above chance in the shortest route task.

Experiment 3 examined the question of attention. Surprisingly, there were no differences between the three experimental groups, such that the addition of an orienting task did not improve or hinder performance in the shortest route test. These results suggest that attending to paths in the environment does not contribute to graph learning, at least when idiothetic information and decision-making are available. The relationship between attention and decision-making may be complex. Since all of the participants in that experiment were free to make decisions about their exploration, an additional attentional task may not have made a contribution beyond decision-making. However, these findings are consistent with the idea that decision-making may influence graph

learning by directing attention. Repeating Experiment 3 with the Guided Walking condition could test this hypothesis. An ongoing study is currently examining the effects of attention on survey knowledge.

Finally, examination of the errors and biases in these experiments might prove revealing about how participants learned the environment and what properties they used during the test phase. In Experiment 2, it was reported that participants often made the same types of errors, often switching the locations of two objects that were at the end of similarly-shaped branch hallways. This pattern was also observed in Experiment 3. For example, participants starting at the snowman often went to the gear when they were supposed to go to the rabbit statue (Figure 1). Similarly, the rabbit and the bookcase were often switched, as were the earth and sink. These results suggest some sort of view-based strategy for final identification of the target object location in the shortest route task. However, in Experiment 1, many of the biases also suggest a similar switching of object locations in the shortcut task. For example, errors for the shortcut from the snowman to the rabbit suggest that participants tended to walk to the location of the gear in this task as well (Figures 6 and 7). This result suggests a bias in the survey knowledge of the maze. It is possible that the views of the hallway alcoves interacted with survey information to create these biases. It is also possible that participants tended to associate certain objects together, and any cognitive map they formed also associated these objects together.

In sum, both idiothetic information and active decision-making are components of “active” learning. The effects of attention, however, still need further investigation before drawing solid conclusions.

Individual Differences in Spatial Learning

Throughout these experiments, marked individual differences appeared. Performance ranged from a participant in the Guided Video condition who was able to perform the shortcut test fairly accurately even without idiothetic information during exploration, to people in the Free Walking condition who only found one or two targets, despite having full information during exploration and a qualitative task. Thus, the experimental results do not imply that all participants will improve their graph knowledge if they make decisions during exploration. Nor do they preclude survey learning in purely visual exploration. However, overall, idiothetic information and decision-making do make a significant contribution to these types of spatial knowledge.

In the examination of individual differences, most noticeably there were significant sex differences in Experiments 1 and 2, with men performing better than women in both the shortcut and shortest route tests. Remarkably, there were no sex differences in Experiment 3. As discussed in Chapter 5, it cannot be determined whether the orienting tasks or the lack of a sex difference in spatial abilities in Experiment 3 accounted for the disappearance of this effect. However, this finding does raise the intriguing possibility that directing attention to the relevant spatial properties might promote equivalent graph learning in men and women.

The results of these three experiments clearly demonstrate that spatial abilities and experiences play a role in spatial learning. Several key measures were correlated with performance across experiments. PTSOT errors, Road Map Test scores, and the two measures of evenness of exploration consistently predicted performance in both the shortcut and shortest route tests. The PTSOT measures the ability to take different

perspectives by mentally rotating the observer's position. The Road Map Test also requires some mental shifting of perspective, by requiring participants to follow a depicted path and report left or right turns without rotating the map. Finally, evenness of exploration requires some ability to know which regions of the maze have been explored and which have not. Uneven explorers often repeatedly went in circles, visiting the same objects over and over again; they might not have been able to rotate their perspective to realize where they had already been. Often, correlations were driven by individuals at the bottom end of the spectrum, such that low errors on the PTSOT or even exploration patterns did not necessarily guarantee good performance in the navigation tasks, but participants who had high errors in the PTSOT or very uneven exploration patterns were unlikely to do well.

Other measures of spatial abilities and experiences seldom correlated with navigation performance. Current video game use was correlated in the overall analysis of the shortest route test in Experiment 2, but did not appear anywhere else. It is possible that video game use was particularly relevant for participants in the Video conditions (Richardson, Powers, & Bousquet, 2011). Current use of navigational video games was correlated with shortcut performance in the Free Walking group, but did not appear anywhere else. Navigational video games may be relevant to survey learning because explorers need to learn the layout of complex environments so that they can take novel shortcuts between locations during gameplay. Notably, men had more video game experience than women in almost all of the types of gaming experience in all three experiments. If video game use is related to navigation performance, then it might help account for the sex differences observed in these experiments.

Other measures of individual difference are notable for their lack of correlation with performance on the experimental tasks. The SBSOD self-reported sense-of-direction was only correlated with the overall analysis of the shortest route test in Experiment 2, but did not correlate with any of the individual groups analyzed here or the overall analysis in Experiment 1 or 3. It is possible that this measure does not fully reflect the spatial abilities required for these tasks. The other notable exceptions are most measures related to differences in VR experience. Distance traveled, angular rotation, and the number of objects visited during the learning phase did not correlate with performance in any experiment. Experience of nausea and feelings of immersion generally did not correlate with performance, although each related to performance in one analysis.

It is important to note that while some of these measures can highlight differences between good and poor navigators, they do not necessarily fully explain the mechanisms behind those differences. For example, exploring the maze evenly has proven to reliably predict performance in both the shortcut and shortest route tests. It is not known, however, if even exploration relies on spatial abilities, spatial learning strategies, or both. Presumably, a navigator must have a certain level of spatial ability to know where they have explored and where they have not, but learning strategies may be reflected in other patterns, such as exploring in a clockwise circle or making sure that all other objects have been visited before returning to the starting object. Additional analysis of exploration patterns might reveal how spatial learning strategies relate to the encoding process, and in turn, how they contribute to graph and survey learning. In addition, other aspects of learning might be important for encoding the spatial information. For example, some

navigators might verbally mediate their exploration more than other participants or make more explicit predictions about each turn. These experiments did not set out to address individual thought processes during exploration, and thus may not have the necessary data to draw any conclusions regarding these aspects from the data, although some strategies might be revealed by examining exploration patterns.

Finally, the discussion of individual differences must be related back to the broader question of active and passive navigation. The four measures identified here as consistent contributors to spatial learning tend to have a common thread involving mental rotation to adopt different viewpoints. Perspective-taking may aid performance on both the shortcut and the shortest route tests because participants are dropped into the maze during the test trials and have to determine where they are facing. It is possible that these measures reflect a fourth component of active learning, the mental manipulation of spatial information. There is some evidence that this ability contributes to spatial learning, but it was not directly investigated here.

Future Directions

The experiments in this dissertation have systematically examined the contributions of idiothetic information and decision-making to survey and graph knowledge, and investigated the effects of attention on graph knowledge. However, a number of open questions remain that future experiments could address.

Attention. The issue of attention deserves further consideration. First, it is important to examine how attention affects survey knowledge. An experiment is in progress to complete the design begun in Experiment 3, with participants given orienting tasks to direct attention to the graph structure or the survey information of the maze.

Attention may be more likely to affect survey learning than graph learning, on the assumption that acquiring metric structure requires more effortful encoding than weaker graph structure.

The interaction between attention and decision-making is also an important consideration. In Experiment 2, participants who were free to make decisions during exploration performed better on the graph test than those who not. It is possible that decision-making serves to direct attention to relevant properties of the environment. In contrast, in Experiment 3, additional orienting tasks did not appear to contribute to graph learning. It is possible that a stronger manipulation of attention was needed. Experiment 3 could be repeated with more explicit instructions to attend to the paths between objects or the spatial configuration of the objects. It is also possible that this was a ceiling effect, due to the contribution of decision-making. One way to address this question would be to present Graph and Survey orienting tasks to participants in the Guided Walking condition, without the freedom to make decisions. In addition, given that decision-making played no role in survey learning in Experiment 1, it remains possible that attention to metric relations could facilitate the acquisition of survey knowledge in the ongoing experiment.

Finally, the issue of attention could be examined with a somewhat different approach, by examining to which aspects of the environment navigators spontaneously attend. Such data could be collected through the use of an eye tracker to record where participants are looking. Preferentially looking at landmarks, for example, rather the paths of the maze might indicate that participants are forming associations that will be important for navigation. Correlations could then be performed between looking

locations and performance in the task. Such an experiment might require a less sparse environment, with more landmarks in the hallways.

Duration of learning. An issue related to attention is that of experience.

Although participants in Experiment 3 were given some experience with the test task, it is possible that they did not know what aspects of the environment were important to attend to until after they had many test trials. It may also be possible that participants could learn the metric survey structure of the environment, but need more time to learn the environment. Thus, a future study could either provide more time in the learning phase or additional sessions. In particular, having experience with the test task may alter how participants explore the environment on subsequent learning phases. There may, however, be a limit to the acquisition of graph or survey knowledge, regardless of additional experience.

Another possible experiment relates the duration of experience with the independence of graph and survey knowledge. Such an experiment might test participants until they achieved nearly perfect graph knowledge, and then test them on survey knowledge and compare their performance to those who were repeatedly tested on survey knowledge. Such an experiment might provide some insight into the extent that metric distances and angles are learned while attending to graph knowledge.

Individual differences. The large individual differences observed in all three experiments suggest that spatial navigation is a highly variable behavior. Further exploration of individual differences could examine whether individual differences in navigation are fixed, or depend on experience. Training with multiple sessions would see whether people continue to improve or have inherent limits (see Ishikawa & Montello,

2006). It is possible that differences in the precision of vestibular and proprioceptive perception could account for some of the individual differences seen here, especially with regard to the shortcut task. Thus, it is worth examining how these factors interact. Finally, the individual difference measures relating to the evenness of exploration might provide insight into how exploration is related to graph and survey knowledge, and further consideration is needed to see how this factor relates to other measures of individual difference.

The role of active mental manipulation of spatial information could also prove a fruitful avenue of research. Participants could be asked to mentally manipulate aspects of the maze during the learning phase. For example, participants might stand at one end of a hallway, and then have to name the objects in the hallway in order starting from the other end of the hallway. Such a task would require explorers to take a different mental perspective, which could facilitate both graph and survey learning.

The present experimental manipulations could also be applied to atypical navigators. For example, Experiments 1 and 2 examined the contributions of idiothetic information, beyond that of vision alone. However, blind and other low-vision navigators must learn environments without access to vision. Perhaps the contributions of idiothetic information are more important to these navigators, or perhaps decision-making and attention make larger contributions. Similarly, those with brain disorders that might lead to difficulty in learning certain aspects of the environment, such as patients with hippocampal damage or Parkinson's Disease, might benefit from idiothetic information or decision-making differently than healthy adults. "Active" navigation

might have different meanings depending on the information that is possibly available to the explorer for use in spatial navigation.

Neural correlates. There are a number of interesting neural correlates of spatial learning. However, current imaging techniques do not allow for physical movement, making many comparisons of active and passive spatial navigation impossible. It may be possible to examine active navigation in other ways, by testing participants in environments they have previously learned with differing amounts of information. Manipulations of decision-making and attention might be more straightforward to implement in desktop VR, which might make tests of graph knowledge during neuroimaging feasible.

In addition, the neural correlates of spatial navigation have often focused on the comparison of route and survey knowledge, but these terms are often confounded in the neural literature. Presently, route knowledge is typically associated with activity in the caudate and parahippocampus, and survey knowledge with activity in the hippocampus. One might expect different neural systems to learn different types of spatial knowledge, however, there may also be a large degree of overlap in the information and processes in graph and survey knowledge which have not been adequately tested in the neural literature. The types of knowledge tested in behavioral work (landmark, route, graph, survey) may not be appropriate categories to examine how the brain works, because neural processes may not break down along these lines. For example, taking the shortest route and making a novel shortcut both require identifying and locating the target, making it difficult to interpret imaging results that might show activity in multiple conditions. Clarification of how neural correlates relate to these forms of spatial

knowledge is needed, by determining which aspects of navigation are common to multiple types of spatial knowledge and which are specific to route, graph, or survey knowledge.

Conclusions

This dissertation began with several questions about active and passive navigation: Are there systematic differences between active and passive spatial navigation? If so, what are the differences in the resulting spatial knowledge? What constitutes “active” exploration specifically – the physical activity of self-motion and its sensory-motor consequences, or the cognitive activity of choosing a route or attending to and encoding particular aspects of the environment? How are survey and graph knowledge affected by active navigation? This dissertation aimed to address these questions by investigating how the mode of exploration in a new environment influences the resulting spatial knowledge.

This dissertation aimed to assess the contributions of several components of active navigation to different types of spatial knowledge. Specifically, three experiments tested the contributions of idiothetic information, cognitive decision-making, and attention to graph and survey learning. The first hypothesis was that idiothetic information contributes to survey knowledge. The second hypothesis was that active decision-making would contribute to graph knowledge. The third hypothesis was that the allocation of attention to relevant environmental properties would contribute to both survey and graph knowledge. The results provide several conclusions regarding the original questions and hypotheses.

First, consistent with hypothesis 1, idiothetic information contributes to both survey and graph learning. Walking during exploration was associated with significantly lower angular errors and variable errors compared to learning with visual information alone. The effects of decision-making in the shortest route test were most prominent in the presence of idiothetic information.

Second, consistent with hypothesis 2, making decisions about exploration only contributes to graph knowledge. There was no evidence to suggest that decision-making contributed to survey learning in any condition.

Third, contrary to hypothesis 3, attention-orienting tasks do not appear to contribute to graph learning. Under conditions with free decision-making and full idiothetic information, participants who were informed about the shortest route test and given an orienting task to direct their attention performed equally well as those who were given no orienting information. Moreover, participants who were incorrectly oriented to a survey test performed just as well as the other groups. Participants may have been at ceiling because decision-making already directed their attention to graph information.

Finally, individual differences in spatial abilities are a factor in both graph and survey learning. In particular, spatial abilities related to perspective-taking and exploring an environment evenly tended to be correlated to performance in both tests of spatial knowledge. These spatial abilities could be related to the mental manipulation of spatial information component of active learning. Perspective-taking may have helped in the shortcut and shortest route tasks in both the learning and test phases.

In sum, there do seem to be systematic differences between active and passive spatial learning. The term “active” is used inconsistently in the literature, with several

possible components. The present findings demonstrate that idiothetic information and decision-making should both be considered important components of active learning; the role of attention remains to be clarified. However, they do not contribute equally to graph and survey knowledge; as expected, qualitative decision-making contributes to graph learning, whereas metric idiothetic information contributes to survey learning. Active exploration is an important part of spatial learning, and the components of active learning must be clearly defined and tested using different types of spatial knowledge to have a more complete understanding of spatial navigation.

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Appendix 1 (compressed for space)**Please take a few minutes to answer the following questions**

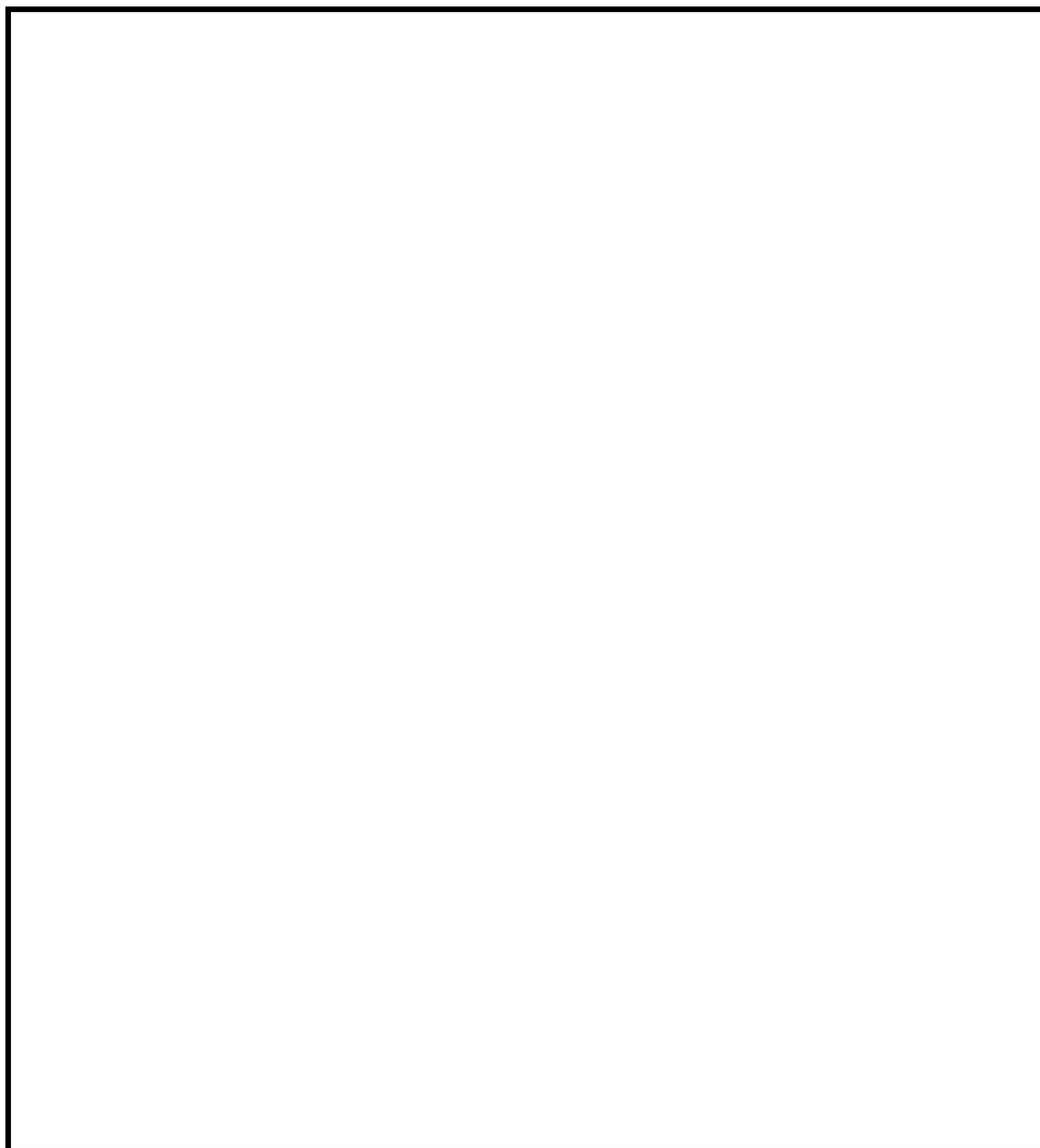
Do your best to draw a map of the virtual environment here, including the objects, paintings, and paths of the maze. Try to be as accurate as possible, but only spend 5-10 minutes.

List of Objects

Bookcase	Rabbit
Clock	Sink
Earth	Snowman
Gear	Well

List of Paintings

Dali (the weird one)
Monet (the reddish seascape)
Magritte (the one with the cat)
Van Gogh (the one with purple flowers)



TURN OVER
MORE QUESTIONS ON BACK

Did you use any conscious strategies to help you remember the locations of the objects while learning your way around the maze? Please describe.

Did you use any conscious strategies during the test phase, when you started at one object and were asked to go to a target object's location? Please describe.

Did you learn anything new about the maze during the test phase? Please describe.

How aware were you of your location and orientation in the real environment (the lab) while you were walking around in the virtual world?

Did you notice anything unusual about the maze? Were some objects harder to find than others?

How immersed did you feel in the virtual environment?

not at all 1 2 3 4 5 6 7 very immersed

Did you experience any dizziness or nausea while wearing the head-mounted display?

none 1 2 3 4 5 6 7 very nauseous

The following statements ask you about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle “1” if you strongly agree that the statement applies to you, “7” if you strongly disagree, or some number in between if your agreement is intermediate. Circle “4” if you neither agree nor disagree.

1. I am very good at giving directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things.

strongly agree strongly disagree

1 2 3 4 5 6 7

3. I am very good at judging distances.

strongly agree strongly disagree

1 2 3 4 5 6 7

4. My “sense of direction” is very good.

strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

strongly agree strongly disagree

- | | | | | | | | | |
|---|---|---|---|---|---|---|---|-------------------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 6. I very easily get lost in a new city. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 7. I enjoy reading maps. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 8. I have trouble understanding directions. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 9. I am very good at reading maps. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 10. I don't remember routes very well while riding as a passenger in a car. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 11. I don't enjoy giving directions. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 12. It's not important to me to know where I am. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 13. I usually let someone else do the navigational planning for long trips. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 14. I can usually remember a new route after I have traveled it only once. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 15. I don't have a very good "mental map" of my environment. | | | | | | | | |
| strongly agree | | | | | | | | strongly disagree |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |

Please circle the best answer for each of the following questions, or write your answer in the space marked "other."

1. Have you ever played video games? Yes No

2. Do you currently play video games? Yes No
3. How long have you been playing video games?
 a. 6 months b. 1 year c. 2-5 years d. 5-10 years e. 10 or more years
4. How often (approximately) do you currently play video games?
 a. daily b. weekly c. once a month d. once in 6 months e. once a year
 f. never
5. How good do you feel you are at playing video games?
 a. very good b. moderately good c. not very skilled d. no skill
6. Approximately how many hours per week do you currently spend playing video games that involve **learning the layout of virtual environments** (e.g. Halo, Goldeneye, World of Warcraft)?
 a. 0 b. 1-5 c. 6-10 d. 10-15 e. 16-20 f. 20+
7. If you do not currently play these sorts of video games, was there a period in your life when you did? If so, please give an age range: _____ to _____
8. How many hours per week did you spend playing these games during that period?
 a. 0 b. 1-5 c. 6-10 d. 10-15 e. 16-20 f. 20+
9. What are your Top 5 (in order) video games that you like to play?
1. _____ 4. _____
2. _____ 5. _____
3. _____
10. Circle your Top 3 genres, or video game categories, that you enjoy playing.

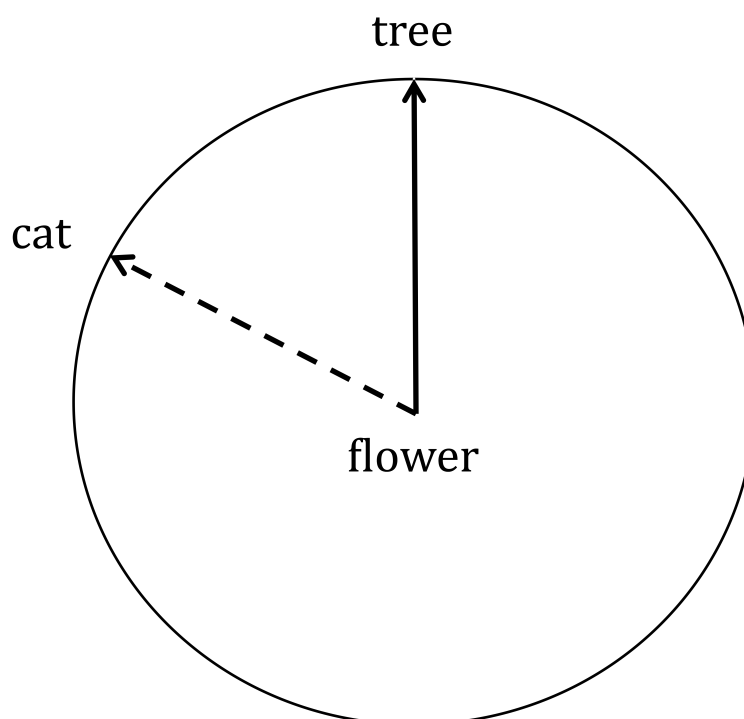
Action	Military	Adventure
Fighting	Space	Arcade
First-person shooter	Strategy	Educational
Role-playing	Strategy wargames	Maze
Mass. Multi. Online Games	Real-time and turn-based strategy	Music
Simulators	Real-time and turn-based tactical	Pinball
Flight	City-building games	Platform
Racing	God games	Puzzle
Sports	Economic simulation games	Stealth
Survival/Horror	Vehicular combat	Other
(specify)		

PTSOT (Example)



Example:

Imagine you are standing at the **flower** and facing the **tree**.
Point to the **cat**.



Road Map Test: Participants followed the path starting in the lower right, naming left or right turns at each corner, without turning the paper or their heads.

