Acquisition and Development of Spatial Knowledge during Wayfinding

By

Qiliang He

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Approved:

Timothy McNamara, Ph.D.

John Rieser, Ph.D.

Randolph Blake, Ph.D.

Robert Bodenheimer, Ph.D.

Alexander Klippel, Ph.D.

i

Abstract

In this dissertation, we investigated the ways in which the acquisition and development of spatial knowledge are affected by 1) the type of spatial relations predominately experienced during learning (routes vs. straight-line paths between locations), 2) environmental complexity and 3) the availability of rotational body-based information. Participants learned the layout of the environment in a virtual shopping mall by repeatedly searching for target storefronts located in one of the buildings. We created two novel learning conditions to encouraged participants to use either route knowledge (routes connecting the storefronts) or survey knowledge (direct, straight-line spatial relations between the storefronts) to find the target, and measured the development of route and survey knowledge in both learning conditions. Environmental complexity was manipulated by varying the alignment of the buildings with the enclosure. Body-based information was manipulated by having participants perform the experiment in front of a computer monitor or in a head-mounted display. After navigation, participants pointed to various storefronts from a fixed position and orientation. Results showed that the frequently used spatial knowledge could be developed comparably across environments with different complexities, but the infrequently used spatial knowledge was less developed in the complex environment. Furthermore, rotational body-based information facilitated spatial learning under some conditions. Our findings further reveal the mechanisms of spatial knowledge acquisition and transfer, and have implications for designing training paradigms that could improve people's navigational efficiency.

Key words: Spatial Knowledge; Wayfinding; Object Penetrability; Environmental Complexity; Body-based Information

Table of Contents

Chapter 1

Introduction

We go to different places every day, and our spatial knowledge of these places develops with more exposures to these locations. Suppose that you move to a new city to start a new job: You may remember the landmarks near home and the workplace first, and then start to learn the route from home to work and vice versa by associating appropriate actions with the landmarks along the way (e.g., turn right at the supermarket). After living in this area for some time, you are not only able to travel from home to work while talking over the phone, but also can travel along a different route when a detour is required. Moreover, you can tell tourists that the museum is 3 miles northeast to the train station. In this dissertation, we aim to investigate the acquisition of different types of spatial knowledge when people navigate in a new environment. Specifically, we try to answer three questions: 1) when people rely on a specific type of spatial knowledge in wayfinding, how does this reliance affect the acquisition of the other type of spatial knowledge? 2) How is the acquisition of the spatial knowledge affected by the environmental complexity? 3) How is the acquisition of spatial knowledge affected by the availability of body-based information?

The categorization of spatial knowledge, as well as the transition from one type of spatial knowledge to another, has attracted substantial research interest in the spatial cognition literature. Siegel and White (1975) proposed that spatial knowledge could be categorized as landmark, route and survey knowledge. Landmark knowledge in their theoretical framework refers to the identity of the objects or scenes that are salient and used for location identification. Route knowledge refers to landmark-action associations (i.e., turn right at the supermarket), which enable one to travel from one place to another along a specific route. Survey knowledge refers to the knowledge of the metric relations between different locations in the environment, which is a map-like representation of the environmental layout (e.g., the museum is 3 miles northeast to the

train station). In addition to the categorization of spatial knowledge, Siegel and White (1975) also proposed that as people learned more about their environment, they transitioned from one type of knowledge to another, with landmark knowledge as the starting phase and survey knowledge as the ultimate phase. In other words, one cannot acquire survey knowledge before sufficient landmark and route knowledge are acquired.

Although the categorization of spatial knowledge from Sigel and White's (1975) account is still widely accepted, the spatial knowledge developmental trajectory has received many challenges from recent research. Taylor et al. (1999) showed that the navigational goal could affect participants' representation of spatial layout. In their study, participants learned a new environment either by studying a map or by navigating on foot. During the learning phase, participants were instructed either to learn the layout of the environment or to learn the fastest route between locations. Taylor et al. (1999) found that irrespective of the learning method (map or navigating), participants who had the goal of learning the layout performed better in the survey knowledge test whereas participants who had the goal of learning the fastest route performed better in the route knowledge test, suggesting that the order of the spatial knowledge acquisition can be influenced by which aspect of the environment people pay attention to. Münzer et al. (2012) found that when exploring a new environment, participants who used a mobile GPS device that displayed the spatial information at ground-level had better route knowledge but worse survey knowledge than participants who used the same device but in which the device displayed the spatial information from an aerial-level. In addition, when the presentation of the map was oriented based on the real-time facing orientation of the navigator, participants had better route knowledge but worse survey knowledge than when the map was always oriented to the north. Both Taylor et al.'s (1999) and Münzer et al.'s (2012) findings suggest that how people learn the environment affects which type of spatial knowledge was learned first or faster. Conducting their study in desktop virtual environment, Buchner and Jansen-Osmann (2008) found that although participants were only asked to learn the landmark-action associations (i.e., turn left or right at the supermarket), the metric information about the route (e.g., distance traveled along a path) was also learned at the same time, and their finding suggests that survey knowledge can be acquired implicitly at the very early stage of spatial navigation. Finally, Ishikawa and Montello (2006) showed that the acquisition of landmark, route and survey knowledge could occur simultaneously after the first exposure to an unfamiliar

2

surrounding for some individuals, and similar findings were reported in other studies conducted in real and virtual environments (Schinazi et al., 2013; Weisberg et al., 2014). Taken together, recent studies suggest that the acquisition of spatial knowledge is continuous rather than stage-like, and is more flexible than what Siegel and White (1975) proposed.

Individual differences in acquisition of spatial knowledge, especially of survey knowledge, also have received much attention. Ishikawa and Montello (2006) conducted a longitudinal study to investigate spatial knowledge acquisition in a large-scale environment with a fixed navigation route. The experimenters drove participants in a car in an unfamiliar surrounding weekly for ten weeks, and measured participants' landmark, route and survey knowledge after each weekly exposure to the environment. Participants' landmark and route knowledge almost reached ceiling after the first ride, but their survey knowledge on average was inaccurate and showed very little improvement across the 10 weeks of study. When they examined individual developmental patterns, Ishikawa and Montello found that some participants were quite accurate after the first one or two sessions and maintained this high level of performance, whereas some participants' survey knowledge was poor and never showed much improvement. The other half of the participants showed steady but not dramatic improvement during the whole study. These results suggest that at least in a large-scale environment where free exploration is not allowed, people's ability to integrate spatial information varies greatly.

To study the nature of the marked individual differences in acquisition of spatial knowledge, Weisberg et al. (2014) conducted a study similar to Ishikawa and Montello (2006) but in a desktop virtual environment. In their study, participants first navigated two disconnected routes and then navigated another two routes that connected the first two routes (similar to Ishikawa & Montello, 2006). After the learning phase, participants were placed at one of the landmarks in a route and were asked to point to another landmark, which could be in the same (within-route pointing) or in a different route (between-route pointing). Weisberg et al. observed substantial individual differences in this task and categorized participants into three groups based on their pointing performance: Good between/Good within, in which participants performed well in both between and within-route pointing; Bad between/Good within, in which participants performed poorly in between-route pointing, but well in within-route pointing; and Bad between/Bad within, in which participants performed poorly in both between and within-route

pointing. No participants performed well in between-route pointing, but poorly in within-route pointing. Weisberg et al. (2014) also correlated the pointing performance with a number of self-report spatial measures and objective spatial and non-spatial measures. They found that a unique portion of the individual differences could be accounted for by the self-reported sense of direction measure (Santa Barbara Sense of Direction Scale, SBSOD, Hegarty et al., 2002). Wen et al. (2011) suggested that people who scored high on the SBSOD used different components of working memory in survey knowledge learning than did people who scored low on the SBSOD. In addition, Schinazi et al. (2013) found that size of the right posterior hippocampus was postivitely correlated with survey knowledge test performance, whereas the gray matter volume in the caudate was negatively correlated with it.

The distinction between route and survey knowledge, as well as individual differences in spatial knowledge acquisition, have received some support in neuroscience studies, although some researchers have argued that a large common brain network is involved in both route and survey knowledge encoding. Animal models identified a dual-memory system in which the hippocampus was involved in place learning and caudate nucleus was involved in response learning (Packard & Knowlton, 2002; O'Keefe & Nadal, 1978; Packard & McGaugh, 1996). Place learning refers to a process in which a navigator learns where the destination is within the environment, whereas response learning refers to a process in which a navigator only learns a sequence of responses (turns along a route) to the destination, but not where the destination is located within the environment. Route and survey knowledge can be considered the products of response and place learning, and both response and place learning can contribute to either type of spatial knowledge. Echoing the results from animal studies, neuroimaging studies on humans showed that increased activation in the hippocampus was associated with better performance in a wayfinding task which required survey knowledge (Hartley at al., 2003), and strategies focusing on route and survey learning were correlated with activation in the caudate nucleus and hippocampus, respectively (Bohbot, et al., 2007; Iaria et al., 2003; Marchette et al., 2011). Wolbers et al. (2004) found that an increase in route knowledge was associated with increased activation in the posterior inferior parietal regions. In addition, Wolbers and Büchel (2005) instructed participants to use survey encoding to represent the layout of the environment and found that the increase of survey knowledge was associated with increased activation in the bilateral retrosplenial cortices. On the other hand, Shelton and Gabrieli (2002) observed that both

route and survey encoding recruited a large common network of brain areas, albeit with some differences in each type of spatial encoding. Latini-Corazzini et al. (2010) came to similar conclusions as did Shelton and Gabrieli (2002), and suggested that the strategies used to solve the route and survey task could also affect the neuroimaging result. For a review of the neural evidence for the categorization of the spatial knowledge, see Boccia et al. (2014) and Chrastil (2013).

To further enhance the understanding of route and survey knowledge acquisition, it is informative to decouple route and survey knowledge and observe how use of one type of knowledge affects the other. Whereas it is straightforward to have people navigate to acquire the route knowledge of the environment while ignoring the survey knowledge, it is very difficult to implement the opposite: having people navigate to acquire the survey knowledge while ignoring the route knowledge. For example, in studies where a map or similar navigational aid was used to promote the acquisition of survey knowledge (Münzer et al., 2012, 2016), participants could not go to places in a straight line and had to convert the survey information from the map to route information to find the place. As a result, the extant research cannot examine how the reliance on survey knowledge in wayfinding affects the acquisition of route knowledge. In this dissertation, we manipulated object penetrability to solve this issue. When objects in the environment were impenetrable, the wayfinding task was the same as those in extant research, in which participants had to go around obstacles to find the target; when the objects were penetrable, the visual presentation and stimuli remain unchanged, but participants could go through obstacles to find the target. Therefore, participants did not need to stay on the road and route knowledge was not necessarily involved in the object penetrable trials. Furthermore, we can study the specificity and transfer of spatial learning in this novel paradigm by having participants predominately perform one type of trial (impenetrable or penetrable), and occasionally having them perform the other type of trial. If learning is specific, then we would observe improvement in the primary but not secondary trials; if learning can be transferred, then we would observe improvement in both types of trials. Specificity and transfer of learning have been studied extensively in perceptual learning (Ahissar & Hochstein, 1997, 2004), but is rarely examined in spatial navigation.

Another benefit of the object penetrability manipulation is the learning-testing compatibility. Among the previous studies of spatial navigation, the measure of the route knowledge was either the navigational performance (Newman et al., 2007; Ruddle et al., 2011), which was fully compatible with the learning method, or other measures which were not fully compatible with the learning method (Taylor et al., 1999). However, in past studies, the testing of survey knowledge was rarely fully compatible with the learning method. The most often used methods in survey knowledge measurement were the pointing and map drawing tasks. In the pointing task, participants were presented or teleported to one of the locations in the environment, and pointed to another location which could not be seen from the current perspective. In the map drawing task, participants needed to place the landmarks and draw the routes between these landmarks in a map in which only the enclosure was outlined. Because wayfinding does not require pointing or map drawing, these two tasks may not be able to fully reflect the survey knowledge acquired through wayfinding (Franks et al., 2000; Morris, Bransford, & Franks, 1977). The object penetrable trials can be used during learning and testing, and therefore make the learning and testing of survey knowledge fully compatible.

In terms of the nature of the spatial knowledge measured by the impenetrable and penetrable trials, we consider that both route and survey knowledge could be involved in both types of trials. We assumed that as participants navigated in impenetrable trials, they would primarily acquire route knowledge but also would acquire at least some survey knowledge, both from following routes in the impenetrable trials (e.g., Ishikawa & Montello, 2006) and from the penetrable trials, in which they experienced some straight-line distances and directions directly. By contrast, we assumed that as participants navigated in the penetrable trials, they would primarily acquire survey knowledge but because participants needed route knowledge to complete the impenetrable trials, they would also acquire some route knowledge as well. For brevity, we refer to the spatial knowledge measured by the impenetrable trials as route knowledge, and to the spatial knowledge measured by the penetrable trials as survey knowledge, but emphasize that these are relative terms.

In addition to investigating how learning condition influences the acquisition of spatial knowledge, we also measured individual differences in the ability to navigate in large-scale environments. In this sense, the SBSOD scale is relevant to our study. SBSOD is a self-report

questionnaire that measures people's judgments about their spatial abilities. There are fifteen items in this scale, and an example item would be "I am very good at giving directions – (strongly agree) 1 2 3 4 5 6 7 (strongly disagree)". A number of studies have shown that SBSOD is reliable and correlates well with navigational tasks that require survey knowledge (Hegarty et al., 2002, 2006; Ishikawa & Montello, 2006; Li & Klippel, 2016; Wen et al., 2011), especially when the task is difficult (Weisberg et al., 2014). In addition, we used a subset of the Sense of Direction and Spatial Representation Scale (SDSR, Pazzaglia & Beni, 2001), which is a self-report measure of spatial ability that focuses on the strategy (landmark, route or survey information) people prefer in wayfinding. An example item would be "When you are in a natural, open environment (mountains, seaside, country), do you naturally individuate cardinal points, that is where north, south, east, and west are? (not at all) 1 2 3 4 5 (very much)". Finally, the Extended Range Vocabulary Test-V3 (Ekstrom et al., 1976), a measure of verbal ability, was administered as a measure of discriminant validity. For each question, participants needed to select the word which had the closest meaning to the given target word from five words. Participants needed to complete 24 questions in 6 minutes.

Spatial navigation has to occur within an environment, and the second topic in this dissertation is the role of environmental complexity in wayfinding. Ruddle et al.'s (2011) study showed that when the environmental layout was configured as a regular, grid-like shape, participants' route knowledge improved rapidly after a small number of exposures, and their survey knowledge was also very accurate. On the other hand, if the navigation occurred in a complex environment with limited exposures, people's wayfinding performance improved with practice, but their survey knowledge showed little improvement and was inaccurate (Hölscher et al., 2005; Li & Klippel, 2016; Ruddle & Péruch, 2004; Wolbers et al., 2004). For example, Hölscher et al. (2005) found that visitors who had visited a complex building at least twice before had better route knowledge of this building than novices, but their survey knowledge was no different from the new visitors. Ruddle and Péruch (2004) had participants explore a maze-like virtual environment, and found that although participants' wayfinding performance increased with trials, their survey knowledge remained rather poor throughout. One exception is Li and Klippel's (2016) study, in which they found that experienced library staff showed better route and survey knowledge than newly enrolled students, but these staff had worked in the library for at least one year. Taken together, it seems that the acquisition of route knowledge is

not much affected by environmental complexity, but the survey knowledge development is very limited in complex environment. However, few studies systematically examined the development of route and survey knowledge in environments of different complexities. In the current project we used the newly developed learning conditions to address this issue.

Space syntax is a set of theories and techniques to conceptualize and quantify the configuration of a spatial layout (Hillier & Hanson, 1984; Hillier & Iida, 2005). Space syntax has a large influence on research in environmental psychology, geography and urban planning, and is a promising method to enhance our understanding of the relationship between environmental properties and human behavior (Montello, 1996; Penn, 2003). In this dissertation, we measured the visibility, connectivity and layout density of the experimental environments to indicate the overall environmental complexity, as in Li and Klippel (2016). Visibility was measured via visibility graph analysis (VGA; Turner et al., 2001), which is a method to analyze the visibility of locations in the space, and can be considered as a measure of how well one can see other locations from each location in the environment. Connectivity was measured via axial map or fewest axial lines (Hillier & Hanson, 1984), which analyzes how one route is connected to other routes in the environment. Layout density was measured by inter-connection density (ICD; O'Neill, 1991), which is the ratio of the number of intersections (a place which has more than two possible directional changes in the environment) and the number of connections among these intersections. The difference between axial maps and ICD is that axial maps measure the continuous structure of open space whereas ICD does not. For example, the ICDs in Figure 1A and B are the same (4), but the fewest axial line is four in Fig. 1A and is two in Fig. 1B.
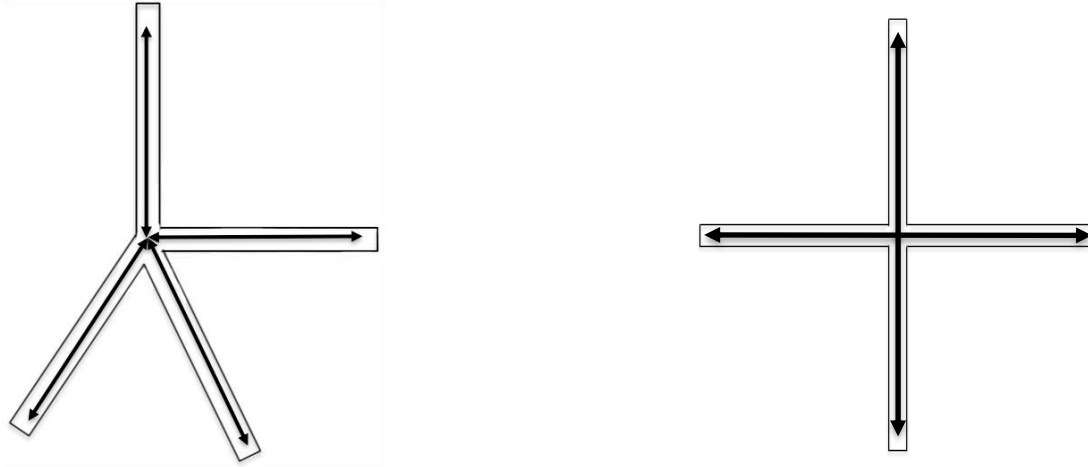
Figure 1. Environments with the same ICDs (4) but different fewest axial lines (4 on the Left and 2 on the Right)

Based on the three space syntax methods just described, we created three environments of different VGA by manipulating the alignment of the buildings with the enclosure while keeping the fewest axial lines and ICD constant across environments (Figure 2). In the aligned environment, all buildings were aligned with the enclosure (Fig.2A); in the half-aligned environment, four out of nine buildings were aligned with the enclosure, and the rest were misaligned by 45° with the enclosure (Fig.2B); in the misaligned environment, all buildings were misaligned by 45° with the enclosure (Fig.2C). The comparisons of the visibility, connectivity and layout density across environments are presented in the Method section.
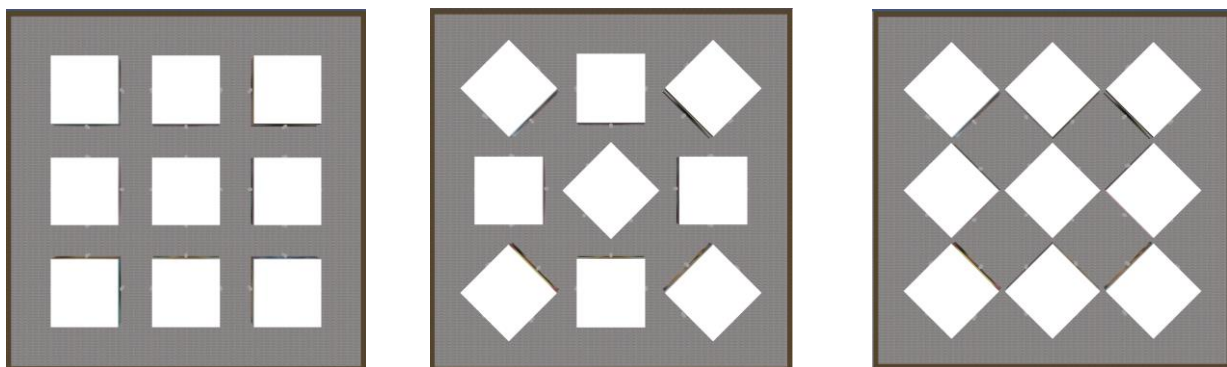

Figure 2. Environments with different layout complexities. Left) Aligned environment. Middle) Half-aligned environment. Right) Misaligned environment

Following Montello (1993), we considered the environment to be large-scale. According to Montello, the scale of an environment can be categorized as figural, vista, environmental and geographical. Figural space is smaller than the body. Vista space is defined as a space that can be viewed from a single vintage point without locomotion (e.g., bedroom). Environmental space is larger than body, and one must locomote to apprehend the entire space. Examples of environmental space are buildings and neighborhoods. Geographical space is much larger than the body, cannot be apprehended through locomotion, and must be learned through symbolic representations, such as maps. The size of the virtual environment in the current project fell in the environmental scale category, and hence we consider it large-scale.

How people navigate in the environment could also affect the acquisition of spatial knowledge, and the third topic in this dissertation is the role of body-based information in wayfinding. Body-based information refers to the internal sensory information provided by the physical movement of the navigator. Body-based information can be categorized as translational information, which is the information about traversed distance, and rotational information, which is the information about the angle of rotation. Ruddle et al. (2011) conducted a systematic study to investigate the role of body-based information in acquisition of spatial knowledge. In the first experiment, they implemented a virtual marketplace of small scale and had participants search for four objects in the first trial, and search for them again in the second trial. In the second trial, however, when participants found a target object, they needed to immediately face or point to the starting location and to the other three objects, and to judge the respective distances from that location. Ruddle et al. (2011) had three experimental groups: Vision group, in which participants sat in front of a computer monitor and used a joystick to navigate, and hence they had only optic flow and no body-based information; 2) Rotational group, in which participants donned a head-mounted device (HMD) and used a joystick to translate but needed to rotate their body to change their orientation. Participants in this group had optic flow and rotational body-based information; 3) Full walking group, in which participants donned an HMD and physically walked in the virtual space. Participants in this group had optic flow, translational and rotational body-based information. Ruddel et al. found that participants in the full walking group had better wayfinding performance and survey knowledge than those in the vision and rotational groups, and that there was no significant difference between the vision and rotational group, suggesting that the rotational body-based information did not affect the spatial knowledge acquisition. In the

second experiment, Ruddle et al. used the same task but expanded the scale of the virtual environment, and added a translational group, in which participants donned an HMD, walked on a linear treadmill (they could only go forward and could not side step) and changed the orientation by joystick. They found that participants in the full walking and translational group had better route and survey knowledge than the vision and rotational groups, and again no significant differences between vision and rotational group. They concluded that in terms of body-based information, the translational component is the major contributor in spatial knowledge acquisition, especially in a large-scale environment.

Whereas translational information seems to be critical in large-scale environment navigation, rotational information is important in small-scale environments (Ruddle, 2013). For example, Klatzky et al. (1998) demonstrated that in a small-scale environment, participants performed better with rotational body-based information than participants without it, and that performance in the rotational condition was as good as that in the full walking condition. In Riecke et al.'s (2010) study where participants needed to memorize the positions of several objects in a number of potential locations, the researchers found that full walking and rotational conditions were better than the vision condition, and no significant difference was found between the walking and rotation conditions. These findings imply that rotational body-based information was sufficient for navigation in a small environment, and the translational information provided no additional benefit.

Based on the aforementioned findings from the studies conducted in the small-scale and large-scale environments, it seems plausible that translational information is more important in large-scale environments whereas rotational information is more important in small-scale environments. However, one caveat is that the environmental layout in Ruddle et al.'s (2011) study was highly regular with distinct features, so participants might have preferred to orient themselves by visual information because body-based information is typically noisier (Chen, McNamara, Kelly, & Wolbers, 2017). In Klatzky et al.'s (1998) and Riecke et al.'s (2010) studies, however, visual orientation cues were absent so rotational body-based information became important in orienting. It is possible that environmental complexity could affect the role of rotational body-based information: in the environment where people cannot orient by visual information alone, rotational body-based information could become very useful. In this

11

dissertation, we investigated this issue by having participants perform the wayfinding task with or without body-based rotational information in environments with different complexities.

To conclude, three main factors, namely the learning condition, environmental complexity and body-based information, were examined to reveal their individual effects and interactions in spatial knowledge acquisition. Besides these factors, individual differences, namely the gender, self-report spatial ability, spatial representation preference and verbal ability, were also taken into account to predict navigational performance.

<center>**Chapter 2**</center>

<center>**Experiments**</center>

Experiment 1

<u>Participants</u>

One hundred and seven participants from Vanderbilt University and the Nashville community participated in Experiment 1, either for course credit or monetary compensation. Eleven participants (nine females) withdrew from the experiment due to motion sickness, leaving ninety-six participants (forty-eight females) in the data analysis. Each experimental condition (6 in total) had 16 participants (eight females).

Before the experiment, all participants completed the Santa Barbara Sense of Direction Scale (SBSOD), a subset of the Sense of Direction and Spatial Representation Scale (SDSRS) and the Extended Range Vocabulary Test-V3.

<u>Material and Design</u>

Environments

Three virtual shopping malls of different complexities were created (Figures 1 & 3) using Sketchup and rendered in Vizard software (WorldViz, Santa Barbara, CA). The graphics were rendered at a resolution of 1920 X 1080 with the diagonal field of view approximately 110°. The buildings were placed in a 3 X 3 grid in the aligned environment. The half-aligned environment was created by rotating five of the buildings in the aligned environment by 45°, and the misaligned environment was created by rotating all of the buildings in the aligned environment by 45°. Other than the rotations, all features were identical among the three environments. Each

<center>13</center>

virtual environment consisted of a 50 m X 50 m enclosure. Each building was 10 m (length) X 10 m (width) X 3 m (height) and had a unique storefront on each side. Most of the storefront textures were materials from Newman et al.'s (2007) study. This resulted in 4 X 9 = 36 unique storefronts. One storefront from each building was selected as the potential target storefront, resulting in nine potential target locations. All participants navigated to the same set of target storefronts, but the order was randomized for each participant. A gray pole in front of each storefront served as the event-trigger object; that is, participants were only considered to have reached a storefront when they collided with the pole in front of that storefront. The floor of the virtual environment was textured with a repeating tile pattern and the wall was textured with a repeating brick pattern. The sky was textured with a sky dome. The environment was a between-subject factor.

Figure 3. Snapshots of virtual environments in the aligned (Left), half-aligned (Middle) and misaligned (Right) environments from the participants' view. The spaces between buildings were sufficiently large in all environments to allow participants to navigate between them

The spatial properties for each environment are tabulated in Table 1. The global VGA value for each environment was analyzed using DepthMapX software (Turner, 2004). Connectivity was measured by the number of fewest axial lines in the environment (Hillier & Hanson, 1984). Layout density was measured by ICD (O'Neill, 1991), a ratio of the number of intersections to the number of connections between these intersections. Connectivity and layout density were identical across environments.

Table 1. Spatial properties for each virtual environment

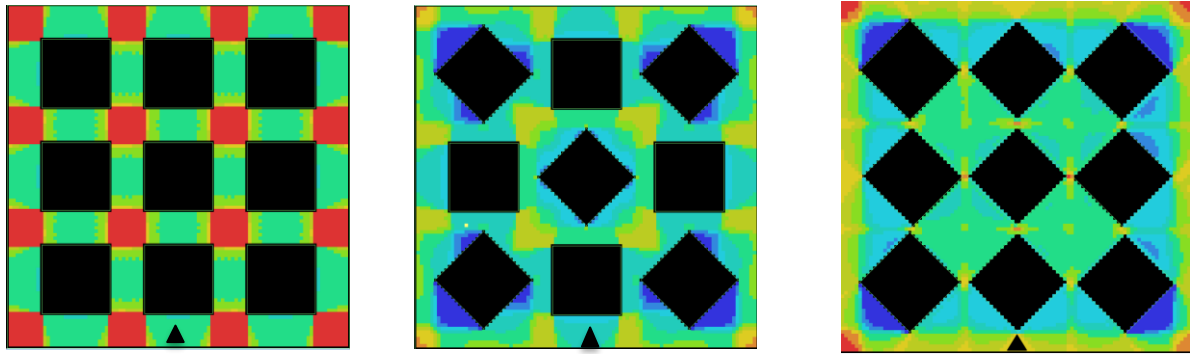|	Aligned	Half-aligned	Misaligned
No. of Buildings Aligned with Enclosure	9	4	0
Visibility (measured by VGA)	1279	933	789
Connectivity (measured by fewest axial lines)	8	8	8
Layout density (measured by ICD)	3	3	3

Figure 4. Visibility analysis for each environment. Warmer colors correspond to higher visibility. The triangle at the bottom of each panel represents the starting location and orientation

Learning Conditions.

The learning conditions (i.e., route or survey learning) were manipulated between participants, resulting in six experimental groups (2 learning methods X 3 environments). Each experimental group had sixteen (eight females) participants, and each participant finished with six practice trials and four blocks of thirteen testing trials. After the navigation, they performed eighteen pointing trials.

Dependent Variables.

Excessive distance and excessive time were used to measure participants' performance in the navigation trials. Excessive distance was defined as,

(actual traversed distance – optimal distance) / optimal distance.

Optimal distance was computed differently in the impenetrable and penetrable trials: for impenetrable trials, the optimal distance was the distance of the shortest route between two locations, which was computed by DepthMapX; for penetrable trials, the optimal distance was the Euclidean distance between two locations. Excessive time was defined as,

(actual traversed time – optimal time) / optimal time.

Optimal time was defined as,

optimal distance / maximum linear speed.

In Experiment 1, the maximum linear speed of the joystick was approximately 5.4 m/s. Pointing error and pointing latency were used to measured pointing task performance.

Procedure

In Experiment 1, participants sat in front of a 21.5-inch computer monitor and used a joystick (Logitech Extreme 3D pro) to perform the tasks. Participants were instructed that there were nine buildings in the virtual shopping mall and their task was to find the designated storefronts repeatedly throughout the experiment, using the shortest path and as quickly as possible. Participants were also told that the buildings would be penetrable in certain circumstances (see the following paragraph), and if buildings were penetrable, they should navigate to the target storefront in a straight-line. The name of the current target storefront appeared at the upper right corner of the screen.

Route Learning Condition

In the route learning condition (Figure 5A), participants used a joystick to navigate in one of three virtual environments from ground level. The first nine trials of each block were impenetrable trials (i.e., buildings were impenetrable), and these were followed by four penetrable trials (i.e., buildings were penetrable, but the enclosure and the poles were still impenetrable). The only difference between impenetrable and penetrable trial was the building penetrability. When participants passed through the wall of a building, the four storefronts of that

building became invisible but the storefronts of the other buildings remained visible. Participants had to traverse the extent of the building (although it was not visible) to exit it. The penetrated building became visible again once participants exited it. Whenever the penetrability status was changed, a 20-second mandatory rest would be triggered, and participants would be informed what the next penetrability status would be. If the buildings were penetrable, participants were encouraged to go to the target locations in a straight line. After the rest, participants were teleported to the starting location to start the next trial. The teleportation only occurred when the penetrability status changed (eight times in total). Each participant finished with thirty-six impenetrable trials and sixteen penetrable trials in the route learning condition.

Before beginning the experiment, each participant practiced with six trials in an environment of the same size as in the experimental trials, but with only four buildings. A unique letter (A, B, C, etc.) was on each side of the building and participants were asked to find a specific letter. They first practiced with four impenetrable trials and then two penetrable trials. Participants were required to go inside the buildings to experience the penetration functionality during the penetrable practice trials.
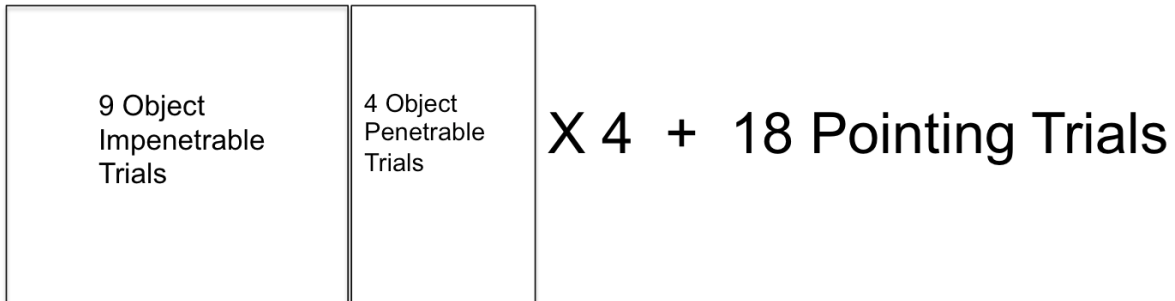
Survey Learning Condition

In the survey learning condition (Figure 5B), the procedure was very similar to route learning condition, except that in the experimental trials, the first nine trials of each block were penetrable trials, and the following four trials were impenetrable trials. Participants finished with thirty-six penetrable trials and sixteen impenetrable trials. In the practice, the first four trials were penetrable trials, and the last two trials were impenetrable trials.

Pointing Task

After completion of the navigation trials, all participants performed a pointing task with two blocks of nine trials. In the pointing task, participants were fixed (i.e., they could not move) at the starting location in the environment (triangle in Figure 4), but they could rotate left or right to see the surroundings to locate themselves. After localization, participants pulled the trigger on a joystick to start the pointing task. The viewing orientation then re-centered to north and from then on, both the position and the orientation were fixed (i.e., a static image). Participants used a

joystick to point to one of the nine target storefronts that had been visited. Participants pointed to each target storefront once in each block.

A.

9 Object Impenetrable Trials	4 Object Penetrable Trials

X 4 + 18 Pointing Trials

B.

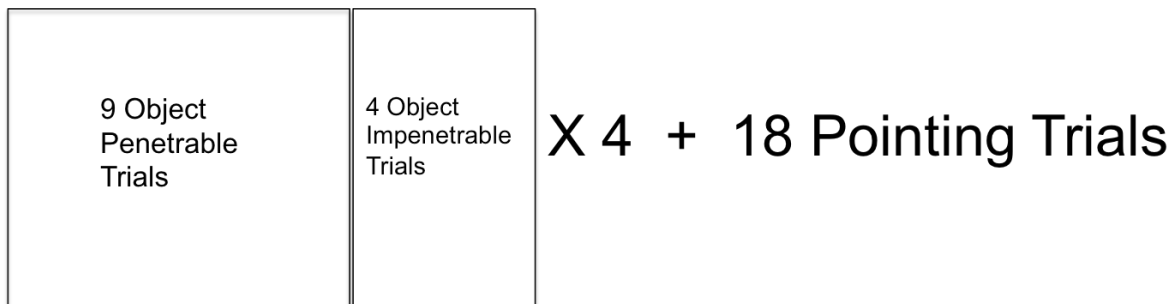| 9 Object Penetrable Trials	4 Object Impenetrable Trials

X 4 + 18 Pointing Trials

Figure 5. Experimental procedure in route (A) and survey (B) learning conditions

Results

We first compared the self-report and ability measures (Table 2) among the six experimental conditions (2 learning conditions X 3 environments). None of these measures differed across experimental groups: SBSOD, $F(5, 95) = .37$, $MSE = 1.33$, $p = .41$, $\eta^2 = .02$; Landmark preference, $F(5, 95) = 1.25$, $MSE = 2.69$, $p = .28$, $\eta^2 = .07$; Route preference, $F(5, 95) = .94$, $MSE = 2.58$, $p = .45$, $\eta^2 = .05$; Survey preference, $F(5, 95) = .37$, $MSE = 3.55$, $p = .86$, $\eta^2 = .02$; Verbal ability, $F(5, 95) = .67$, $MSE = 11.89$, $p = .64$, $\eta^2 = .04$. These results suggest that

18

participants assigned to different conditions on average had similar self-perceived spatial abilities and preferences and similar verbal ability. Further analysis of the individual differences is reported after the comparison between Experiments 1 and 2.

Table 2. Descriptive Statistics for the Self-report Measures and Verbal Abilities.

Exp.1 (Desktop)				Exp.2 (HMD)			
	Range	Mean	SD		Range	Mean	SD
SBSOD	1.06 - 6.93	3.89	1.13	SBSOD	1.20 - 6.87	3.95	1.08
Landmark	4 - 10	7.80	1.65	Landmark	3 - 10	7.95	1.67
Route	3 - 10	6.27	1.60	Route	3 - 10	6.36	1.60
Survey	2 - 10	6.09	1.85	Survey	3 - 10	6.23	1.60
Verbal	4 - 20	14.05	3.41	Verbal	5 - 21	13.63	2.04

Notes: SBSOD = Santa Barbara sense of direction. The possible range is 1 – 7. The higher the score, the better perceived sense of direction. Landmark = Preference for landmark strategy. The possible range is 2 – 10. The higher the score, the more preferred using landmark strategy. Route = Preference for route strategy. The possible range is 2 – 10. The higher the score, the more preferred using route strategy. Survey = Preference for survey strategy. The possible range is 2 – 10. The higher the score, the more preferred using survey strategy. Verbal = Verbal ability. The possible range is 0 – 24. The higher the score, the better the verbal ability

In the navigation trials, the patterns of results on excessive time were very similar to those on excessive distance, and therefore we only present the statistical analysis of excessive distance in the main text, and analysis of the excessive time can be found in the appendix. In addition, because the assumption of sphericity was violated in the majority of the mixed ANOVAs conducted in this research, pairwise comparisons and contrasts on the within-subject factors (blocks and trial type) only used data in the conditions being compared and did not use the pooled mean-square error and associated degrees of freedom (Kirk, 1995). Pairwise comparisons and contrasts on the between-subject factors (environment and learning condition) used the degrees of freedom and mean-square error from the omnibus ANOVA.

Route Learning Condition

In the route learning condition, participants performed 9 impenetrable trials followed by 4 penetrable trials in each block, for 4 blocks (Figure 5A). We first present analyses of the more frequent impenetrable trials, followed by analyses of the less frequent penetrable trials.

Impenetrable trials. Excessive distance of the impenetrable trials was analyzed in a 4 (block) X 3 (environment) mixed-ANOVA (Figure 6). The main effect of blocks was significant ($F(3, 135) = 15.10$, $MSE = 3.28$, $p < .001$, $\eta^2 = .251$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = .246$, $MSE = 5.99$, $p = .783$, $\eta^2 = .011$; $F(6, 135) = .420$, $MSE = 3.28$, $p = .86$, $\eta^2 = .02$). The linear trend contrast across blocks was significant ($F(1, 45) = 22.56$, $MSE = 4.93$, $p < .001$, $\eta^2 = .33$), suggesting that participants' performance in the impenetrable trials was improving over time.

To compare the amount of the acquired route knowledge measured by the impenetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was not significant ($F(2, 45) = .04$, $MSE = 7.53$, $p = .96$, $\eta^2 = .01$). Planned pairwise comparisons showed that none of the comparisons was significant (ts(45) $< .41$, ps $> .68$). These results suggest that participants' spatial knowledge measured by the impenetrable trials improved over time during navigation, and this improvement was comparable across environments.

Penetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted on excessive distance in penetrable trials (Figure 6). The main effect of blocks was significant ($F(3, 135) = 4.67$, $MSE = 2.66$, $p = .004$, $\eta^2 = .094$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = 2.07$, $MSE = 10.64$, $p = .13$, $\eta^2 = .084$; $F(6, 135) = .781$, $MSE = 2.66$, $p = .58$, $\eta^2 = .034$). The linear trend contrast across blocks was significant ($F(1, 45) = 4.67$, $MSE = 2.66$, $p = .004$, $\eta^2 = .09$), suggesting that participants' performance on penetrable trials was improving over time.

To compare the amount of the acquired survey knowledge measured by the penetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was marginally significant ($F(2, 45) = 3.15$, $MSE = 3.15$, $p = .052$, $\eta^2 = .14$). Planned pairwise comparisons showed that participants in the aligned environment

performed significantly better than those in the misaligned environment ($t(45) = 2.51$, $p = .02$), and no other comparisons were significant (ts$(45) < 1.45$, $p > .15$). Furthermore, significant improvement between the first and last blocks only occurred in the aligned environment ($t(15) = 2.82$, $p = .013$), but not in the other two environments (ts$(15) < 1.45$, ps $> .17$).
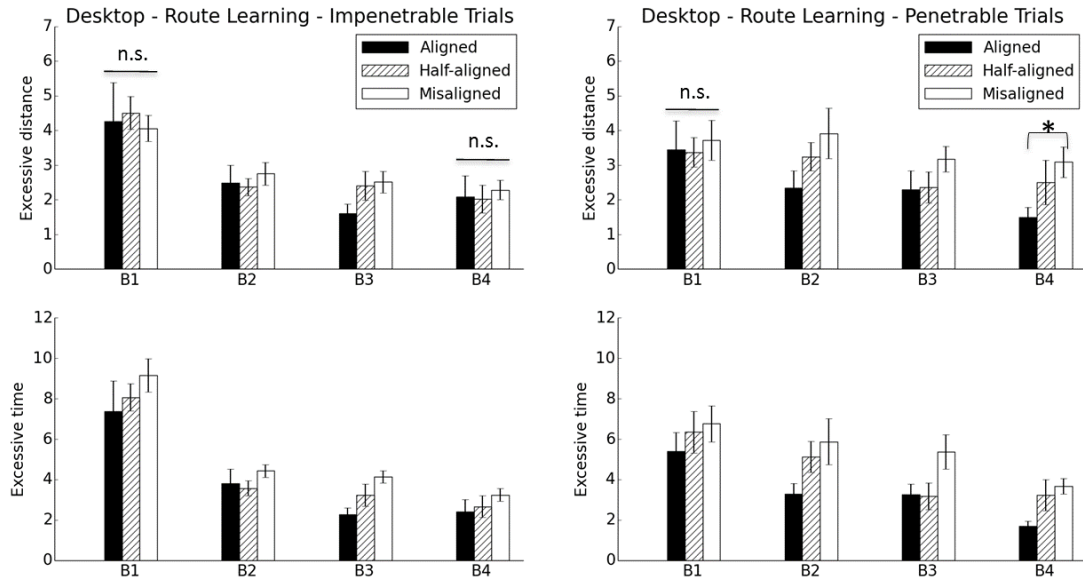

Figure 6. Navigational performance in the route learning condition across three environments in Experiment 1. B1 – B4 stand for Block 1 to Block 4. Left Panels: Performance in impenetrable trials. Right Panels: Performance in penetrable trials. Upper Panels: Excessive distance. Lower Panels: Excessive time

Pointing task. For the pointing task, separate one-way ANOVAs were conducted to analyze pointing error and latency across environments (Figure 8). The environment complexity effect was not significant in pointing error ($F(2, 45) = 2.12$, $MSE = 821.38$, $p = .13$, $\eta^2 = .09$), but was significant in pointing latency ($F(2, 45) = 4.51$, $MSE = 10.04$, $p = .016$, $\eta^2 = .20$). Pairwise comparisons showed that pointing error in the aligned environment was significantly lower than in the misaligned environment ($t(45) = 2.05$, $p < .05$). Pointing latency in the misaligned environment was larger than in the aligned and half aligned environments (ts$(45) > 2.34$, ps $< .03$). Pointing tasks have been traditional measures of survey knowledge (Ishikawa & Montello,

21

2006; Ruddle & Péruch, 2004; Ruddle et al., 2011; Weisberg et al., 2014). The present results demonstrated that participants had better survey knowledge in the aligned than in the misaligned environment, with the half-aligned environment in between.

In summary, results from the route learning condition, where people spent most of the time navigating in an impenetrable environment, showed the following: 1) The spatial knowledge measured by the impenetrable trials was comparable across environments, but the spatial knowledge measured by penetrable trials developed unevenly across environments. There was a significant improvement in the aligned environment, but very little improvement in the half-aligned and misaligned environments. This in turns shows that the spatial knowledge measured by the two types of trials was different, otherwise we would observe the same pattern of results across environments. As discussed in the Introduction, we refer to the spatial knowledge measured by the impenetrable trials as route knowledge, and the spatial knowledge measured by penetrable trials as survey knowledge for brevity. 2) The survey knowledge measured by the penetrable trials and the pointing task was better in the aligned environment than in the misaligned environment, with half-aligned environment in between. This in turns shows that the environmental complexity manipulation was successful: the more aligned the environment was, the better the performance.

Survey Learning Condition

In the survey learning condition, participants performed 9 penetrable trials followed by 4 impenetrable trials in each block, for 4 blocks (Figure 5B). We first present analyses of the more frequent penetrable trials, followed by analyses of the less frequent impenetrable trials.

Penetrable trials. Excessive distance of penetrable trials was analyzed in a 4 (block) X 3 (environment) mixed-ANOVA (Figure 7). The main effect of blocks was significant ($F(3, 135) = 18.24$, $MSE = 3.34$, $p < .001$, $\eta^2 = .288$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = 1.77$, $MSE = 6.32$, $p = .18$, $\eta^2 = .07$; $F(6, 135) = .47$, $MSE = 3.34$, $p = .82$, $\eta^2 = .02$). The linear trend contrast across blocks was significant ($F(1, 45) = 49.27$, $MSE = 3.45$, $p < .001$, $\eta^2 = .52$), suggesting that participants' performance on the penetrable trials was improving over time.

To compare the amount of the acquired survey knowledge measured by the penetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was not significant ($F(2, 45) = 1.10$, $MSE = 2.10$, $p = .33$, $\eta^2 = .05$). None of the planned pairwise comparisons was significant (ts(45) < 1.50 , ps > .15). Collectively, these results suggest that participants' survey knowledge measured by penetrable trials improved during navigation, and this improvement was comparable across environments. This pattern of results was in sharp contrast to the penetrable trials in the route learning condition, in which performance in the aligned environment was significantly better than in the misaligned environment in the last block.

Impenetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted on excessive distance in the impenetrable trials. The main effect of blocks was significant ($F(3, 135) = 6.77$, $MSE = 5.49$, $p < .001$, $\eta^2 = .13$), as well as the main effect of environment ($F(2, 45) = 4.67$, $MSE = 7.72$, $p = .02$, $\eta^2 = .17$). The interaction was not significant ($F(6, 135) = .736$, $MSE = 5.49$, $p = .62$, $\eta^2 = .03$). The linear trend contrasts across blocks ($F(1, 45) = 9.23$, $MSE = 8.567$, $p = .004$, $\eta^2 = .17$) and environments ($F(1, 45) = 5.88$, $MSE = 7.72$, $p = .02$, $\eta^2 = .16$) were both significant, suggesting that performance on the impenetrable trials was improving over time and the more aligned the environment was, the better was the performance.

To compare the amount of the acquired route knowledge measured by the impenetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was marginally significant ($F(2, 45) = 2.81$, $MSE = 2.10$, $p = .07$, $\eta^2 = .12$). Planned pairwise comparisons showed that performance in the aligned environment was significantly better than that in the half-aligned ($t(45) = 2.05$, $p = .046$) and misaligned environments ($t(45) = 2.05$, $p = .045$), but there was no significant difference between the half-aligned and misaligned environments ($t(45) = .20$, $p = .98$). Furthermore, significant improvement between the first and last blocks was only observed in the aligned environment ($t(15) = 3.38$, $p = .004$), but not in the other two environments (ts(15) < 1.62, ps > .12). Again, this pattern of results was in sharp contrast to the impenetrable trials in the route learning condition, in which performance was comparable across environments.
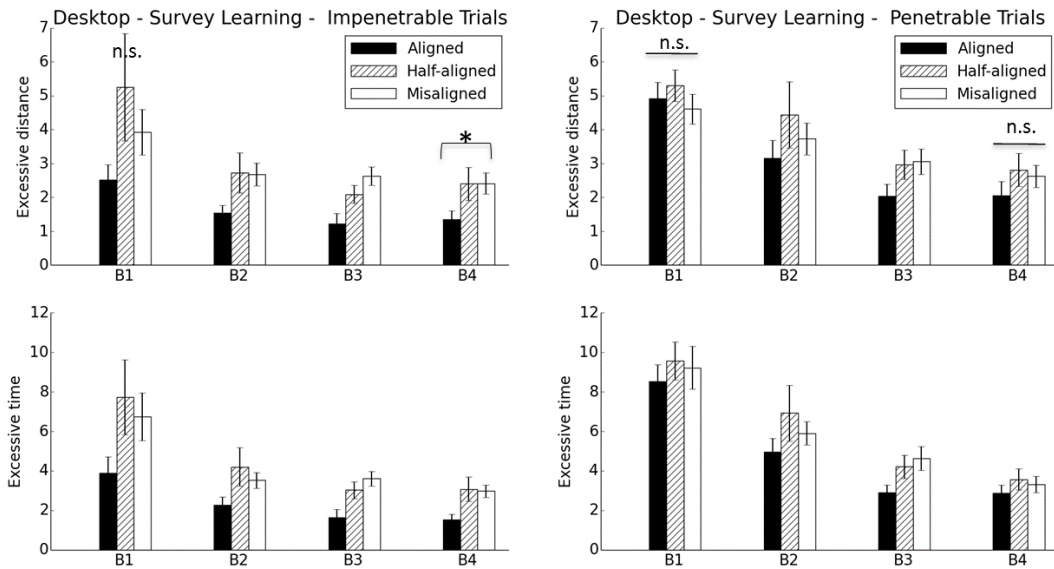
Figure 7. Navigational performance in survey learning condition across three environments in Experiment 1. B1 – B4 stand for Block 1 to Block 4. Left Panels: Performance in impenetrable trials. Right Panels: Performance in penetrable trials. Upper Panels: Excessive distance. Lower Panels: Excessive time

Pointing task. For the pointing task, separate one-way ANOVAs were conducted to analyze pointing error and latency across environments (Figure 8). The environmental complexity effect was significant in pointing error ($F(2, 45) = 3.86$, $MSE = 259.24$, $p =.03$, $\eta^2 = .17$), but not in pointing latency ($F(2, 45) = .10$, $MSE = .12$, $p =.89$, $\eta^2 = .004$). The linear contrast across environments was significant in pointing error ($F(1, 45) = 7.74$, $p =.008$), and pairwise comparisons showed that pointing error was significantly lower in the aligned environment than in the misaligned environment ($t(45) = 2.78$, $p = .008$). These results showed that participants had better survey knowledge in the aligned environment than in the misaligned environment, with the half-aligned environment in between.
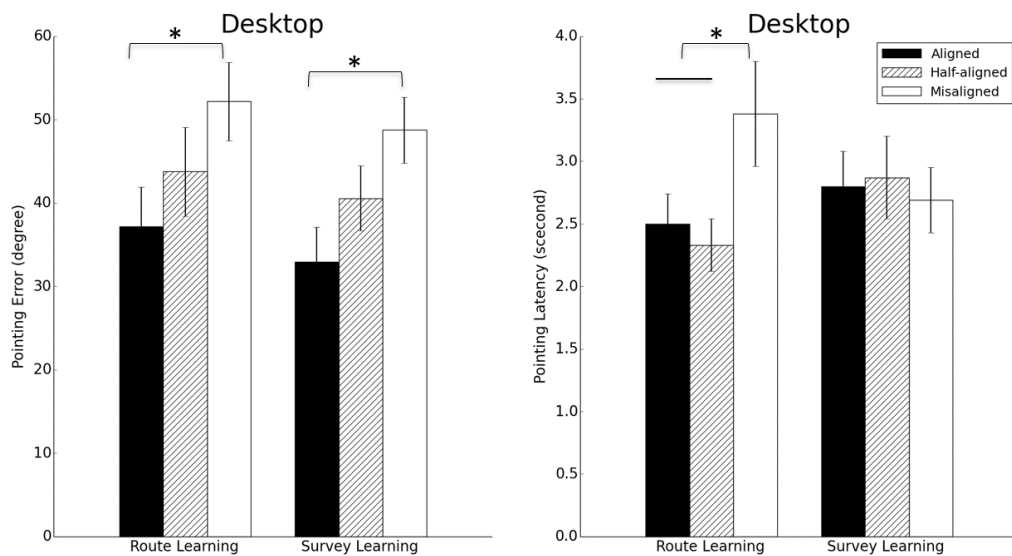
Figure 8. Pointing error (Left) and pointing latency (Right) in the route and survey learning conditions in Experiment 1

The pattern of results in the survey learning condition was the opposite of that in the route learning condition, and this contrast indicates that although the frequently used spatial knowledge could be developed comparably across environments, the infrequently used spatial knowledge was less developed in the misaligned environments. In addition, the development of the infrequently used knowledge only occurred in the aligned environment, but not in the misaligned environment. Taken together, these findings suggest that the acquisition of spatial knowledge was more specific in a complex environment than in a regular environment.

In the following analysis, we examine the interactions between learning condition and trial type within environments: if learning were transferrable, we would observe no interaction (i.e., comparable performance in the impenetrable and penetrable trials regardless of learning conditions); otherwise an interaction should be observed (i.e., performance in the impenetrable trials is better in the route learning condition than in the survey learning condition, and performance in the penetrable trials is better in the survey learning condition than in the route learning condition).

Transfer of Spatial Knowledge

To examine the transfer of spatial knowledge within environments, we compared the navigational performance at the end of the experiment between the route and the survey learning conditions. We took the average of the final four trials of each trial type (impenetrable or penetrable trials) to represent the corresponding spatial knowledge acquired in the respective learning condition (Figure 9). For example, in the route learning condition, route knowledge was represented by the last four trials of the 4th block, and the survey knowledge was represented by the 4th block, which also had four trials.

To investigate the transfer of spatial knowledge within each environment, we conducted a 2 (learning condition) X 2 (trial type) two-way mixed ANOVA for each environment. In the aligned environment, the main effects (learning condition: $F(1, 30) = .16$, $MSE = 6.40$, $p = .68$, $\eta^2 = .006$; trial type: $F(1, 30) = .06$, $MSE = 2.83$, $p = .79$, $\eta^2 = .002$) and the interaction ($F(1, 30) = 1.60$, $MSE = 2.83$, $p = .21$, $\eta^2 = .05$) were not significant. In the half-aligned environment, the main effects (learning condition: $F(1, 30) = .02$, $MSE = 6.92$, $p = .88$, $\eta^2 = .001$; trial type: $F(1, 30) = .20$, $MSE = 3.00$, $p = .65$, $\eta^2 = .007$) and the interaction ($F(1, 30) = .30$, $MSE = 3.00$, $p = .86$, $\eta^2 = .001$) were not significant, either. These insignificant results suggested that the acquisition of spatial knowledge was not specific in the aligned and half-aligned environments.

In the misaligned environment, the main effects were not significant (learning condition: $F(1, 30) = .35$, $MSE = 2.60$, $p = .55$, $\eta^2 = .01$; trial type: $F(1, 30) = 3.38$, $MSE = 1.47$, $p = .07$, $\eta^2 = .10$), but the interaction was significant ($F(1, 30) = 7.73$, $MSE = 1.47$, $p = .029$, $\eta^2 = .29$). The pairwise comparison of route knowledge (as measured by impenetrable trials) between the learning conditions was not significant ($t(30) = .96$, $p = .34$) and the comparison of survey knowledge (as measured by penetrable trials) between the learning conditions was only marginally significant ($t(30) = 1.74$, $p = .09$). The pattern of significant interaction with insignificant main effects suggested that the learning conditions affected the acquisition of route and survey knowledge differently, confirming the previous conclusion that acquisition of spatial knowledge was specific in the misaligned environment.
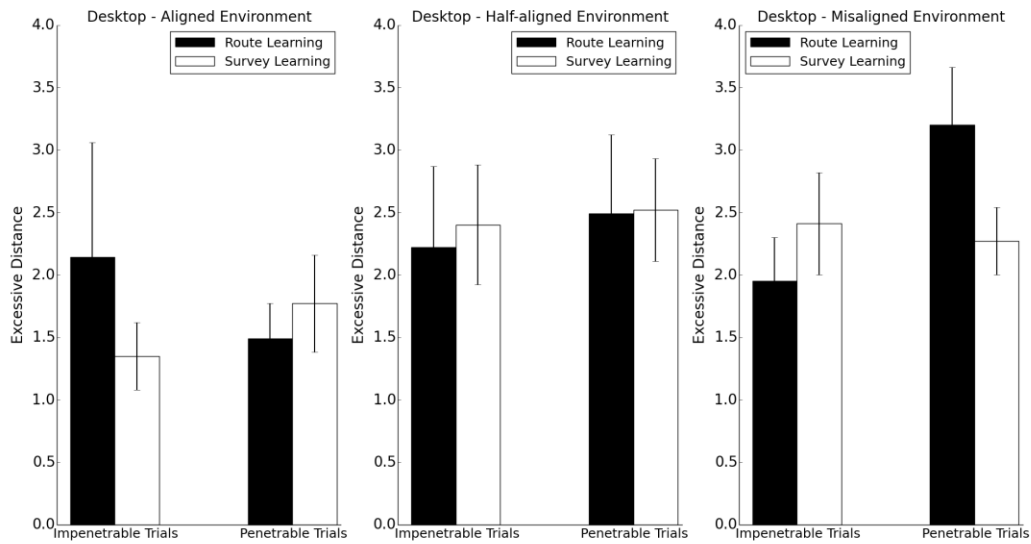
Figure 9. Learning trials performance (excessive distance) in the three environments in Experiment 1. Left) Aligned environment. Middle) Half-aligned environment. Right) Misaligned environment

Finally, we conducted two 2 (learning condition) X 3 (environment) ANOVAs to examine the pointing task performance (Figure 8). For pointing error, neither the main effect of learning condition ($F(1, 90) = 1.11$, $MSE = 322.88$, $p = .29$, $\eta^2 = .01$) nor the interaction was significant ($F(2, 90) = .02$, $MSE = 322.88$, $p = .97$, $\eta^2 = .001$), but the main effect of environment was significant ($F(2, 90) = 5.62$, $MSE = 322.88.$, $p = .005$, $\eta^2 = .12$). Pairwise comparisons showed that pointing error was significantly smaller in the aligned environment than in the misaligned environment ($t(90) = 3.34$, $p = .001$). For pointing latency, none of the effects was significant (learning condition: $F(1, 90) = .05$, $MSE = 1.15$, $p = .81$, $\eta^2 = .001$; environment: $F(2, 90) = 2.83$, $MSE = 1.15$, $p = .06$, $\eta^2 = .06$; interaction: $F(2, 90) = 1.62$, $MSE = 1.15$, $p = .20$, $\eta^2 = .03$).

In summary, the results from comparing learning conditions and trial type in each environment confirmed our previous conclusions: spatial knowledge of different types can be fully transferred in the aligned environment, but transfer was limited in the misaligned environment. The route and survey knowledge acquisition and transfer in the half-aligned environment were somewhere between the aligned and misaligned environments.

27

Experiment 2

Experiment 2 was designed to 1) be compared with Experiment 1 to examine the role of rotational body-based information in spatial navigation in a large-scale environment, and 2) to determine whether the pattern of results in Experiment 1 could be replicated, especially the findings of the route and survey learning conditions across environments. To gain access to rotational body-based information, participants in Experiment 2 donned a head-mounted device (HMD) and rotated their body to change the viewing perspective in the virtual environment (participants in Exp.1 used a joystick to change the viewing perspective). They used a joystick to translate in the virtual environment as did their counterparts in Experiment 1.

Participants

One hundred and six participants from Vanderbilt University and Nashville community participated in Experiment 2, either for course credit or monetary compensation. Ten participants (nine females) withdrew from the experiment due to motion sickness, leaving ninety-six participants (forty-eight females) in the data analysis. Each experimental condition (6 in total) had 16 participants (eight females).

Before the experiment, all participants completed the Santa Barbara Sense of Direction Scale (SBSOD), a subset of the Sense of Direction and Spatial Representation Scale (SDSRS) and the Extended Range Vocabulary Test-V3.

Materials, design and procedure

Experiment 2 was designed to complement Experiment 1 by allowing participants to have rotational body-based information during spatial navigation. The materials, design and procedure were identical to those in Experiment 1 with three exceptions: 1) Participants wore the head-mounted device (HMD; Oculus Rift Consumer Version) to perform the experiment. The

resolution of the HMD was 1080 X 1020 pixels for each eye, with the diagonal field of view approximately 110°. 2) The joystick could only be used for translation. Participants needed to rotate their body to change the viewing perspective. 3) The maximum linear speed was reduced from 5.4 m/s in Experiment 1 to 1.4 m/s in Experiment 2 in order to reduce the possibility of motion sickness.

Results

Route Learning Condition

We first compared the self-report and ability measures (Table 2) across the six experimental conditions. None of these measures differed across experimental groups: SBSOD, $F(5, 95) = 2.01$, $MSE = 1.12$, $p = .08$, $\eta^2 = .11$; Landmark preference, $F(5, 95) = 1.82$, $MSE = 2.70$, $p = .11$, $\eta^2 = .10$; Route preference, $F(5, 95) = .35$, $MSE = 2.66$, $p = .88$, $\eta^2 = .02$; Survey preference, $F(5, 95) = 1.21$, $MSE = 4.13$, $p = .31$, $\eta^2 = .06$; Verbal ability, $F(5, 95) = 1.26$, $MSE = 10.28$, $p = .28$, $\eta^2 = .07$. Again, these results suggest that participants assigned to different conditions on average had similar self-perceived spatial abilities and preferences and similar verbal ability.

As in Experiment 1, the route learning condition and the survey learning condition differed only in the relative frequency of impenetrable and penetrable trials. In the route learning condition, participants completed 9 impenetrable and 4 penetrable trials within each block. We first present analyses of the more frequent impenetrable trials, followed by analyses of the less frequent penetrable trials.

Impenetrable trials. Excessive distance of impenetrable trials was analyzed in a 4 (block) X 3 (environmental) mixed-ANOVA (Figure 10). The main effect of blocks was significant ($F(3, 135) = 49.19$, $MSE = .65$, $p < .001$, $\eta^2 = .522$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = .645$, $MSE = 4.49$, $p = .53$, $\eta^2 = .028$; $F(6, 135) = 1.90$, $MSE = .65$, $p = .085$, $\eta^2 = .078$). The linear trend contrast across blocks was significant ($F(1, 45) = 85.41$, $MSE = 1.00$, $p < .001$, $\eta^2 = .65$), suggesting that participants' performance in the impenetrable trials was improving over time.

To compare the amount of the acquired route knowledge measured by the impenetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was not significant ($F(2, 45) = .09$, $MSE = .93$, $p = .90$, $\eta^2 < .01$). None of the pairwise comparisons was significant (ts$(45) < .42$, ps $> .67$). These results suggest that participants' route knowledge improved over time during navigation, and this improvement was comparable across environments with different complexities.

Penetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted on excessive distance in the penetrable trials (Figure 10). The main effect of blocks was significant ($F(3, 135) = 8.23$, $MSE = 1.37$, $p < .001$, $\eta^2 = .15$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = .17$, $MSE = 3.59$, $p = .83$, $\eta^2 = .008$; $F(6, 135) = 1.01$, $MSE = 1.37$, $p = .41$, $\eta^2 = .043$). The linear trend contrast across blocks was significant ($F(1, 45) = 27.35$, $MSE = 1.02$, $p < .001$, $\eta^2 = .37$), suggesting that participants' performance on penetrable trials was improving over time.

To compare the amount of the acquired survey knowledge measured by the penetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was not significant ($F(2, 45) = 2.38$, $MSE = 1.15$, $p = .10$, $\eta^2 = .10$). Results of pairwise comparisons showed that participants in the aligned environment performed significantly better than those in the misaligned environment ($t(45) = 2.18$, $p = .034$), and no other comparisons were significant (ts$(45) < 1.10$, $p > .27$). Furthermore, significant improvement between the first and last block was only observed in the aligned and half-aligned environments (ts$(15) > 2.56$, ps $< .022$), but not in the misaligned environment ($t(15) = 1.16$, $p = .26$).
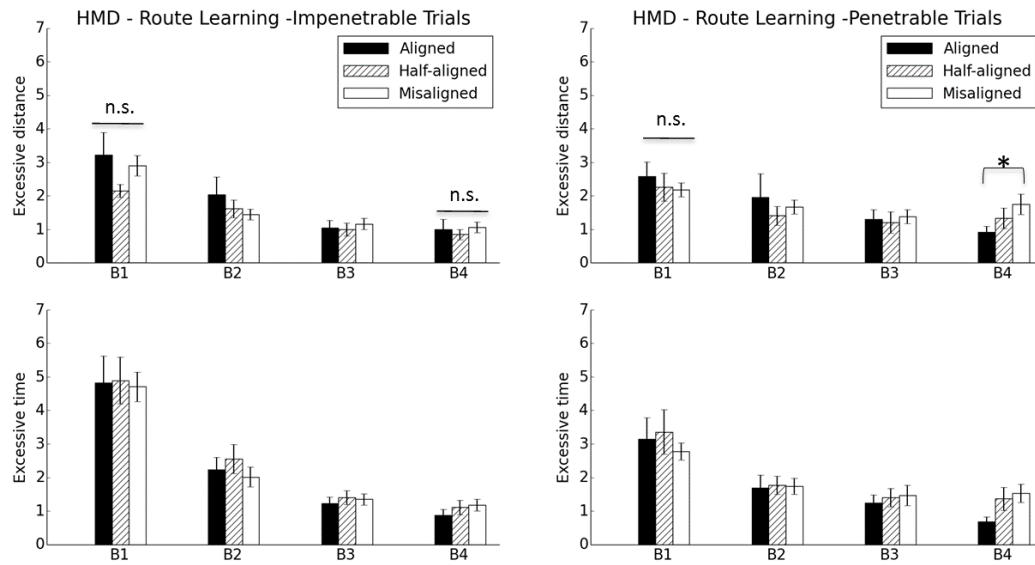
Figure 10. Navigational performance in the route learning condition across three environments in Experiment 2. B1 – B4 stand for Block 1 to Block 4. Left Panels: Performance in impenetrable trials. Right Panels: Performance in penetrable trials. Upper Panels: Excessive distance. Lower Panels: Excessive time

Pointing task. Separate one-way ANOVAs were conducted to analyze pointing error and latency across environments (Figure 12). The environmental complexity effect was not significant in pointing error ($F(2, 45) = .084$, $MSE = 323.94$, $p = .45$, $\eta^2 = .035$), or in pointing latency ($F(2, 45) = .81$, $MSE = 1.71$, $p = .44$, $\eta^2 = .035$). None of the pairwise comparisons on pointing error or latency showed any significant results. (ts $(45) < 1.35$, $p > .18$), albeit the pointing error showed a trend of declining from the misaligned to aligned environments.

Overall, the three patterns of results are very similar to the route learning condition in Experiment 1, which showed that route knowledge developed comparably across environments, but survey knowledge only developed in the more regular environment.

Survey Learning Condition

We first present analyses of the more frequent penetrable trials, followed by analyses of the less frequent impenetrable trials.

Penetrable trials. Excessive distance in penetrable trials, the most frequent trials in the survey learning condition, was analyzed in a 4 (block) X 3 (environment) mixed-ANOVA (Figure 11). The main effect of blocks was significant ($F(3, 135) = 64.32$, $MSE = .59$, $p < .001$, $\eta^2 = .588$), as was the main effect of environment ($F(2, 45) = 8.48$, $MSE = 1.25$, $p = .001$, $\eta^2 = .27$), but the interaction was not ($F(6, 135) = .64$, $MSE = .59$, $p = .69$, $\eta^2 = .02$). The linear trend contrasts across blocks ($F(1, 45) = 129.45$, $MSE = .77$, $p < .001$, $\eta^2 = .74$) and environments ($F(1, 45) = 16.34$, $MSE = 1.25$, $p < .001$, $\eta^2 = .24$) were both significant, suggesting that performance on the penetrable trials was improving over time and the more aligned the environment was, the better was the performance.

To compare the amount of the acquired survey knowledge measured by the penetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was significant ($F(2, 45) = 7.90$, $MSE = 1.44$, $p = .001$, $\eta^2 = .35$). Planned pairwise comparisons showed that performance in the misaligned environment was worse than the other two environments (ts$(45) > 3.19$, ps $< .003$), with no significant difference between the aligned and half-aligned environments ($t(45) = .49$, $p = .61$).

Impenetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted on excessive distance in the impenetrable trials (Figure 11). The main effect of blocks was significant ($F(3, 135) = 12.82$, $MSE = .70$, $p < .001$, $\eta^2 = .22$), as was the main effect of environment ($F(2, 45) = 9.62$, $MSE = 1.47$, $p < .001$, $\eta^2 = .30$), but the interaction was not significant ($F(6, 135) = .25$, $MSE = .70$, $p = .95$, $\eta^2 = .01$). The linear trend contrasts across blocks ($F(1, 45) = 26.87$, $MSE = .94$, $p < .001$, $\eta^2 = .37$) and environments ($F(1, 45) = 16.34$, $MSE = 1.47$, $p < .001$, $\eta^2 = .24$) were both significant, suggesting that performance on the impenetrable trials was improving over time and the more aligned the environment was, the better was the performance.

To compare the amount of the acquired route knowledge measured by the impenetrable trials across environments, we conducted a one-way ANOVA in the last block. The effect of environmental complexity was significant ($F(2, 45) = 9.40$, $MSE = .23$, $p < .001$, $\eta^2 = .41$). Planned pairwise comparisons showed that performance in the misaligned environment was worse than the other two environments (ts$(45) > 2.47$, ps $< .02$), with no significant difference between the aligned and half-aligned environments ($t(45) = 1.85$, $p = .07$). Furthermore,

significant improvement between the first and last blocks was observed in all environments (ts(15) > 2.48, ps < .03).
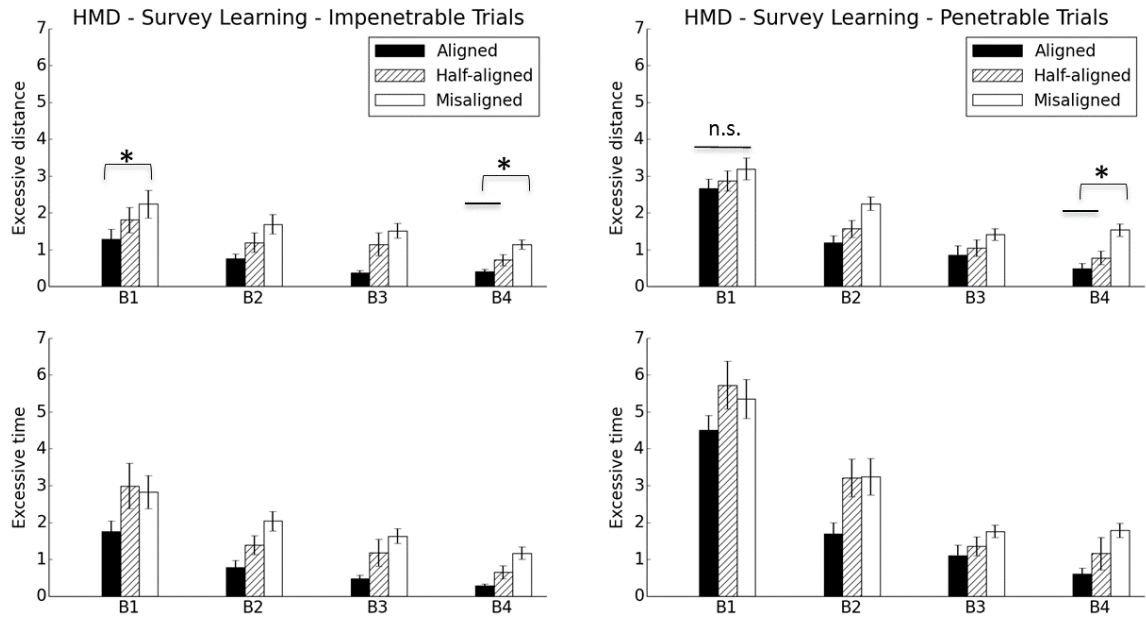

Figure 11. Navigational performance in the survey learning condition across three environments in Experiment 2. B1 – B4 stand for Block 1 to Block 4. Left Panels: Performance in impenetrable trials. Right Panels: Performance in penetrable trials. Upper Panels: Excessive distance. Lower Panels: Excessive time

Pointing task. Separate one-way ANOVAs were conducted to analyze pointing error and latency across environments (Figure 12). The environment complexity effect was significant in pointing error (F(2, 45) = 24.60, MSE = 125.30, p < .001, η^2 = .52), as well as in pointing latency (F(2, 45) = 5.87, MSE = 1.05, p =.005, η^2 = .20). Pairwise comparisons showed that pointing error in the aligned environment was significantly lower than in the half-aligned and misaligned environments (ts(45) > 2.8, ps < .008), and the half-aligned was significantly lower than the misaligned (t(45) = 4.17, p < .001). Pointing latencies were significantly longer in the misaligned environment than in the other two environments (ts(45) > 2.73, ps < .01).
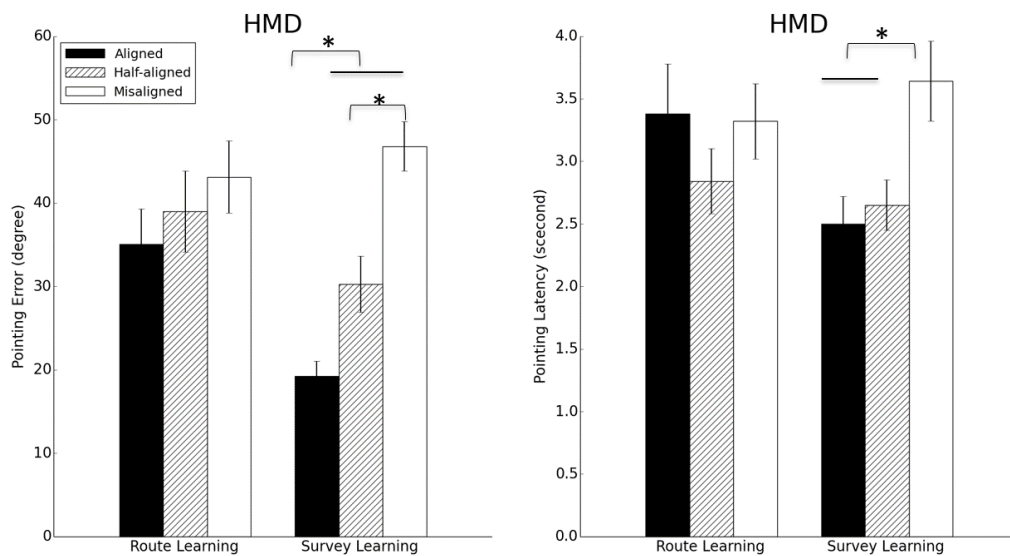
Figure 12. Pointing error (Left) and pointing latency (Right) in the route and survey learning conditions in Experiment 2

The pattern of results in the survey learning condition in Experiment 2 was different from Experiment 1 in that the performance in the aligned environment was very good, outperforming the misaligned environment in each dependent measure. One possible explanation of this difference is that participants in the aligned environment took more advantage of the rotational body-based information than those in the misaligned environment. We discuss this further in the General Discussion.

Transfer of Spatial Knowledge

As in Experiment 1, we computed the average of the final four trials of each trial type (object impenetrable or penetrable trials) to represent the corresponding spatial knowledge acquired in the respective learning condition (Figure 13).

To investigate the transfer of spatial knowledge within each environment, we conducted a 2 (learning condition) X 2 (trial type) two-way mixed ANOVA for each environment. In the

aligned environment, neither the main effects (learning condition: $F(1, 30) = 2.34$, $MSE = 1.16$, p = .13, $\eta^2 = .07$; trial type: $F(1, 30) = .57$, $MSE = .28$, $p = .45$, $\eta^2 = .01$) nor the interaction ($F(1, 30) = .01$, $MSE = .28$, $p = .91$, $\eta^2 < .001$) was significant. In the half-aligned environment, neither the main effects (learning condition: $F(1, 30) = 1.00$, $MSE = 1.79$, $p = .32$, $\eta^2 = .03$; trial type: $F(1, 30) = 2.36$, $MSE = .50$, $p = .13$, $\eta^2 = .07$) nor the interaction ($F(1, 30) = 2.09$, $MSE = .50$, p = .15, $\eta^2 = .06$) was significant. In the misaligned environment, only the main effect of trial type was significant ($F(1, 30) = 23.04$, $MSE = .52$, $p < .001$, $\eta^2 = .43$). Unlike in Experiment 1, we did not observe a significant interaction in the misaligned environment, and inspection of the data suggests that it was largely due to the similar patterns of results between the route and survey learning condition in the misaligned environment (Fig. 13C). We speculate that the lack of interaction in the misaligned environment might be due to participants in the survey learning condition not penetrating the buildings as frequently as their counterparts in Experiment 1. We discuss this possibility further in the General Discussion.

Finally, we conducted two 2 (learning condition) X 3 (environment) ANOVAs to examine the pointing task performance (Figure 12). For pointing error, the main effect of learning condition was significant ($F(1, 90) = 5.19$, $MSE = 224.62$, $p = .03$, $\eta^2 = .05$), as was the main effect of environment ($F(2, 90) = 11.41$, $MSE = 224.62$, $p < .001$, $\eta^2 = .20$). The interaction between learning condition and environment was also significant ($F(2, 90) = 3.43$, $MSE = 224.62$, $p = .04$, $\eta^2 = .07$). Simple main effects showed that the pointing error was significantly lower in the survey learning condition than in the route learning condition in the aligned environment ($t(90) = 2.99$, $p = .004$), but not in the half-aligned ($t(90) = 1.65$, $p = .10$) or misaligned environments ($t(90) = 0.69$, $p = .49$). These results suggested that the advantage of the survey learning condition over the route learning condition decreased as the environment became more complex. For pointing latency, only the main effect of Environment was significant ($F(1, 90) = 3.37$, $MSE = 1.38$, $p = .04$, $\eta^2 = .07$), with participants in the half-aligned environment pointing significantly faster than their counterparts in the misaligned environment ($t(90) = 2.50$, $p = .014$).

Collectively, results from Experiment 2 showed that with rotational body-based information, learning conditions did not seem to affect the acquisition of route and survey knowledge differently. In addition, when we examined pointing task performance in the aligned environments, the survey learning condition in HMD was not only better than the route learning

condition in HMD, but also better than the route and survey learning conditions in Desktop (ts(30) > 2.98, ps < .006). Taken together, it seems the rotational body-based information could facilitate the acquisition of spatial knowledge in the more regular environments.
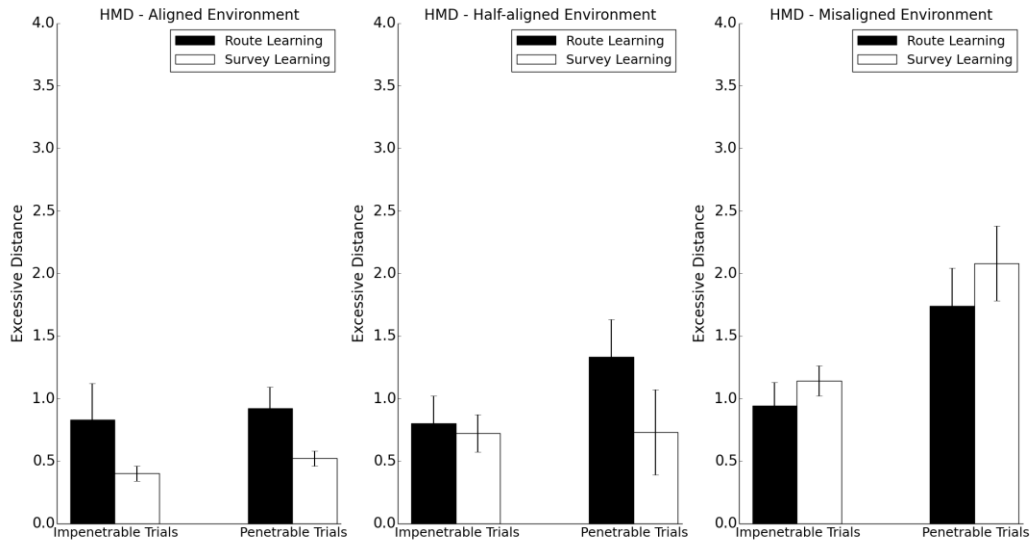

Figure 13. Learning trials performance (excessive distance) in the two learning conditions across environments in Experiment 2. Left) Aligned environment. Middle) Half-aligned environment. Right) Misaligned environment

Control Experiment

Due to the speed differences between Experiments 1 and 2, we were not able to conclude whether rotational body-based information could provide additional benefits in spatial navigation. Therefore, we conducted a control experiment in the Desktop and HMD interfaces with the same speed of 1.4 m/s. The results in Experiment 2 suggested that participants in the survey learning condition of the aligned environment benefited the most from the body-based information, so the control experiment was conducted in the survey learning condition with the aligned environment in the two interfaces (i.e., Desktop-Survey Learning-Aligned Environment vs. HMD-Survey Learning-Aligned Environment).

Sixteen participants (eight females) were recruited for the Desktop condition. The materials, design and procedure were identical to the corresponding condition in Experiment 1 except that the speed was reduced to 1.4 m/s. Another sixteen participants (eight females) were recruited for the HMD condition. The materials, design and procedure were identical to the corresponding condition in Experiment 2. None of the self-report or ability measures differed between these two groups: SBSOD, $t(30) = .56$, $p = .57$; Landmark preference, $t(30) = .13$, $p = .89$; Route preference, $t(30) = .90$, $p = .37$; Survey preference, $t(30) = .53$, $p = .59$; Verbal ability, $t(30) = .48$, $p = .62$.

Penetrable trials. Excessive distance in penetrable trials, the most frequent trials in the survey learning condition, was analyzed in a 4 (block) X 2 (interface) mixed-ANOVA (Figure 14). The main effect of blocks was significant ($F(3, 90) = 29.54$, $MSE = .54$, $p < .001$, $\eta^2 = .50$), as was the main effect of the interface ($F(1, 30) = 5.93$, $MSE = 1.78$, $p = .02$, $\eta^2 = .16$), but the interaction was not ($F(3, 90) = .20$, $MSE = .54$, $p = .89$, $\eta^2 < .01$). The linear trend contrasts across blocks was significant ($F(1, 30) = 52.35$, $MSE = .78$, $p < .001$, $\eta^2 = .63$). These results suggest that performance on the penetrable trials was improving over time, and the rotational body-based information was beneficial to the development of survey knowledge.

Impenetrable trials. A 4 (block) X 3 (interface) mixed-ANOVA was conducted on excessive distance in the impenetrable trials (Figure 14). The main effect of blocks was

significant ($F(3, 90) = 6.83$, $MSE = .27$, $p < .001$, $\eta^2 = .18$), as was the main effect of the interface ($F(1, 30) = 12.82$, $MSE = .53$, $p = .001$, $\eta^2 = .30$), but the interaction was not ($F(3, 90) = .10$, $MSE = .27$, $p = .38$, $\eta^2 = .01$). The linear trend contrasts across blocks was significant ($F(1, 30) = 24.54$, $MSE = .21$, $p < .001$, $\eta^2 = .45$). These results suggest that performance on the penetrable trials was improving over time, and the rotational body-based information was beneficial to the development of route knowledge.
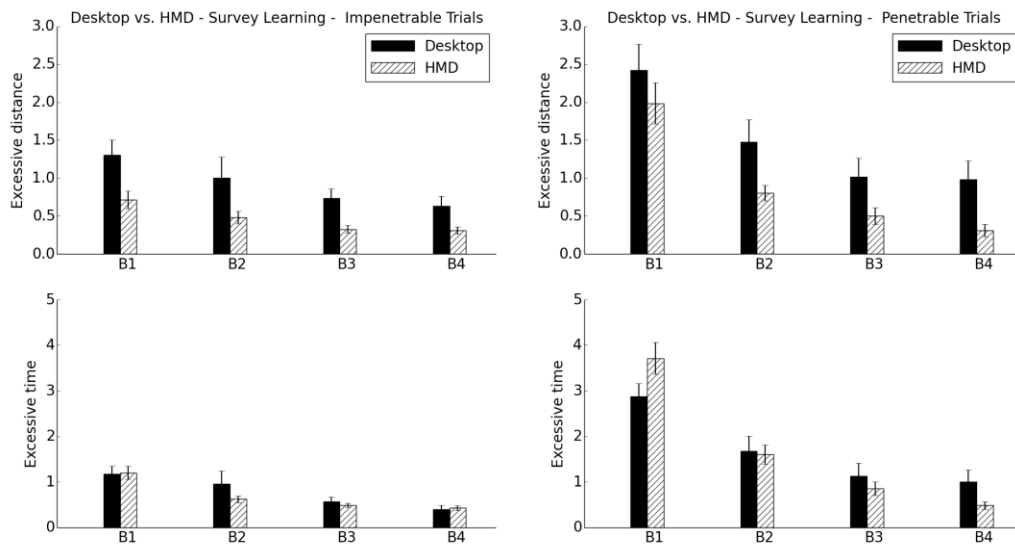
Figure 14. Learning trials performance in Desktop and HMD in the control experiment

Pointing task. Separate independent t tests were conducted to analyze pointing error and latency between interfaces (Figure 15). Neither the pointing error ($t(30) = 1.74$, $p = .09$) or the pointing latency ($t(30) = .85$, $p = .39$) was significant.
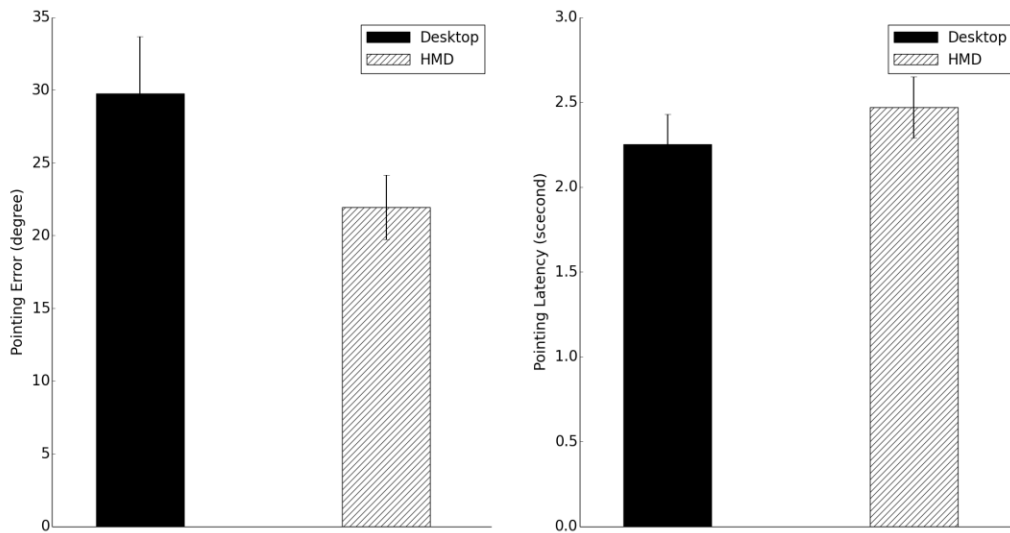
Figure 15. Pointing error (Left) and pointing latency (Right) in the Desktop and HMD in the control experiment

Results from the control experiment clearly demonstrated that rotational body-based information played a role in spatial navigation, at least in the condition where participants could penetrate the buildings most of the time in a well-aligned environment.

Individual Differences

The intercorrelations among the self-report and ability measures (gender; SBSOD; preference of landmark, route, survey; and verbal ability), and the dependent variables (impenetrable trials, penetrable trials and pointing error) are presented in Table 3.

Table 3

Intercorrelations, Means, and Standard Deviations for Self-report, Ability and Performance Measures

Measure	1	2	3	4	5	6	7	8	M	SD
1. Gender	-								1.50	.50
2. SBSOD	-.26**	-							3.92	1.11
3. Landmark	.22**	-.14	-						7.88	1.66
4. Route	-.03	.23**	.09	-					6.32	1.60
5. Survey	-.16*	.56**	-.09	.18*	-				6.17	1.95
6. Verbal	.04	-.01	-.13	-.17*	-.05	-			13.84	3.32
7. Impenetrable	.05	-.13	0.09	-.12	-.19**	.02	-		1.44	1.74
8. Penetrable	-.07	-.13	0.06	-.08	-.12	-.12	.47**	-	1.76	1.60
9. Pointing	.05	-.18*	-.003	-.084	-.18*	-.18*	.52**	.48**	39.13	18.24

*Note. Bivariate correlations, means, and standard deviations for all participants (N = 192) are presented above. For measure 1, higher value indicates female. For measures 2 – 6, higher values indicate higher performance or preference. For measures 7 – 9, higher values indicate lower performance. SBSOD = Santa Barbara sense of direction. Landmark = Preference for landmark strategy. Route = Preference for route strategy. Survey = Preference for survey strategy. Verbal = Verbal ability. Impenetrable = Average excessive distance in the last four impenetrable trials. Penetrable = Average excessive distance in the last four penetrable trials. Pointing = Pointing error. *p < .05. **p< .01*

The results from the intercorrelations among the self-report and ability measures were in line with the literature, with males scoring higher in self-reported sense of direction (Hegarty et al., 2002; Kozlowski & Bryant, 1977) and preferring more to use survey strategies than females in navigation (Sholl et al., 2000; Lawton, 1994) while females preferred more to use landmarks in navigation (Pazzaglia & Beni, 2001). The correlations between the pointing task and the navigational trials averaged .50 (.52 with impenetrable trials and .48 with penetrable trials), suggesting that the pointing task is a strong predictor of navigational performance even though the pointing task involves no locomotion.

Table 3 also revealed a moderately high correlation between SBSOD and the preference of survey strategy ($r = .56$). Due to this collinearity and our goal of wanting to correlate the preferences for landmark, route and survey strategies with navigational performance, we removed the SBSOD instead of the preference for survey strategy in the following analysis.

Because we are more interested in examining the relationships between the self-report measures and the dependent variables, hierarchical multiple regression models were used to control for the influence of the experimental variables (learning condition, environment and interface). We entered the experimental variables into the regression first and then the self-report measures, and the results are shown in Table 4.

Table 4

Hierarchical Regression Models for the Impenetrable, Penetrable and Pointing Task Performance

Measures	Impenetrable			Penetrable			Pointing error	
	Model 1	Model 2		Model 1	Model 2		Model 1	Model 2
Learning	-.02	-.03		-.07	-.08		-.15*	-.15*
Environment	.10	.11		.29**	.29**		.37**	.35**
Interface	-.37**	-.36**		-.33**	-.34**		-.20**	-.20**
Gender		-.01			-.11			.01
Landmark		.10			.09			.07
Route		-.09			-.11			-.03
Survey		-.16*			-.11			-.17*
Verbal		.07			-.12			-.16*
R^2	.14	.19		.20	.25		.20	.26
F	10.57**	5.50**		15.84**	7.66**		15.31**	7.98**
ΔR^2		.50			.05			.06
ΔF		2.24			2.41*			3.08*

Note. Regression analyses with data expressed as standardized betas. Model 1: Only the experimental variables were entered as predictors. Model 2: Experimental variables and self-report measures were entered as predictors. Landmark = Preference for landmark strategy. Route = Preference for route strategy. Survey = Preference for survey strategy. Verbal = Verbal ability. Impenetrable = Average excessive distances of the last four impenetrable trials. Penetrable = Average excessive distances of the last four penetrable trials. Pointing = Pointing error
*$p < .05$. **$p < .01$*

For impenetrable trial performance, self-report and ability measures only explained a marginally significant portion of the variance after the experimental variables were controlled for ($\Delta F(5,183) = 2.24$, $p = .051$). Among the self-report and ability measures, only preference for the survey strategy was significantly correlated with performance on impenetrable trials ($\beta = -.16$) after all the experimental variables and other individual difference measures were controlled for. This result suggests that the more participants preferred to use survey strategy (map-like representation of the space) in spatial navigation, the better their performance on the impenetrable trials.

For penetrable trial performance, self-report and ability measures explained a significant proportion of the variance after the experimental variables were controlled for, but none of these measures was significantly correlated with performance on penetrable trials.

For pointing error, self-report and ability measures explained a significant proportion of the variance after the experimental variables were controlled for. The preference for the survey strategy ($\beta = -.17$) and the verbal abilities ($\beta = -.16$) were significantly correlated with the pointing error after all the experimental variables and other individual difference measures were controlled for. These results suggest that the more participants preferred to use a survey strategy and the better their verbal abilities were, the better their pointing task performance. However, the correlation between these two self-report measures and the pointing error was weak.

Overall, although the individual difference measures predicted a significant proportion of variance beyond the experimental variables, the magnitude was small: The ΔR^2s of the impenetrable, penetrable and pointing error were .05, .05 and .06, respectively. In addition, the magnitudes of the correlations between the significant individual difference measures and the dependent variables were small as well. The variance in the dependent variables can be divided into the proportion explained by experimental conditions and the proportion explained by individual differences, and the experimental conditions only explained 14 – 20% of the variance, which suggests that individual differences were large. In the current study, the self-report and ability measures only explained an additional 5 – 6% of the variance, which indicates that a large proportion of the individual differences was not captured by the self-report and ability measures used in the current study.

Chapter 3

General Discussion

This dissertation was designed to investigate the acquisition and development of spatial knowledge during wayfinding in a new environment. Participants were placed in a virtual shopping mall and were required to find specific storefronts repeatedly. We expected that participants' spatial knowledge of this environment would develop over the course of wayfinding and this development would reflect on their wayfinding efficiency. We manipulated three variables in the wayfinding task, namely the learning condition, environmental complexity and rotational body-based information, to examine the cognitive processes underlying the spatial knowledge acquisition. Results from the two main experiments and the control experiment showed that 1) without rotational body-based information (Exp.1), the spatial knowledge that was used frequently in wayfinding developed comparably across environments with varying degrees of complexity, but the spatial knowledge that was used infrequently was less well developed in the misaligned environment. In addition, the learning conditions affected the acquisition of spatial knowledge in the misaligned environment, but not in the aligned or half-aligned environment. 2) With rotational body-based information (Exp.2), the findings in the route learning condition were similar to those in Exp.1: Route knowledge developed comparably across environments, but survey knowledge was less developed in the misaligned environment. In the survey learning condition, however, both the route and survey knowledge were better developed in the aligned environment than in the misaligned environment. 3) A control experiment that equated the speed of locomotion in the Desktop and HMD conditions showed that rotational body-based information facilitated the acquisition of spatial knowledge at least in the aligned environment under the survey learning condition.

One of the most important contributions from the present study to research on navigation is that we created a new paradigm to circumvent two limitations of the traditional wayfinding

task: 1) low learning-testing compatibility for survey knowledge, and 2) invariant involvement of route knowledge in learning a new environment. In the present study, participants could or could not go through the buildings to reach a target, and these two tasks were referred to as object penetrable trials and object impenetrable trials, respectively. Based on the order and the proportion of the impenetrable and penetrable trials in the wayfinding task, we created two learning conditions: route learning and survey learning. This new paradigm not only provides good learning-testing compatibility, but also allows us to have participants mainly rely on one type of spatial knowledge to solve the wayfinding task while measuring the development of both types of spatial knowledge during the process.

In Experiment 1 where participants did not have rotational body-based information, we found that in the route learning condition, the spatial knowledge measured by the impenetrable trials was comparable across environments of varying degrees of complexity, but the spatial knowledge measured by the penetrable trials was better for the aligned environment than for the misaligned environment. In the survey learning condition, however, the pattern was the reverse: the spatial knowledge measured by the impenetrable trials was better for the aligned environment than the misaligned environment, and the spatial knowledge measured by the penetrable trials was comparable across environments. These two findings suggest that the spatial knowledge measured by the two types of trials are different, otherwise the pattern of results should have been similar or different consistently across environments (e.g., the performance in the aligned environment should have been similar to or better than the misaligned environment regardless of the type of trial). Because participants had to rely on route knowledge to complete the impenetrable trials, we assumed that the impenetrable trials measured a composite of spatial knowledge that is more route knowledge oriented. Similarly, because participants had to rely on survey knowledge to complete the penetrable trials, we assumed that the penetrable trials measured a composite of spatial knowledge that is more survey knowledge oriented.

Another important finding from the route and survey learning conditions in Experiment 1 was that the spatial knowledge corresponding to the less performed trials improved in the aligned environment, but did not improve or barely improved in the misaligned environment. In the route learning condition, the route knowledge improved regardless of the environmental complexity, but the survey knowledge only improved in the aligned environment. This finding is in line with

a number of studies showing that people can find their way in a complex environment efficiently, but still struggle in the task that depends heavily on survey knowledge (Hölscher et al., 2005; Ishikawa & Montello, 2006; Li & Klippel, 2016; Ruddle & Péruch, 2004). The opposite result in the survey learning condition, however, is a novel finding: survey knowledge developed evenly across environments, but not the route knowledge. It further confirms the proposition that the development of spatial knowledge does not necessarily follow the landmark-route-survey pattern (Buchner & Jansen-Osmann, 2008; Ishikawa & Montello, 2006; Münzer et al., 2012; Taylor et al., 1999) proposed by Siegel and White (1975). This finding also reflects the flexibility in human spatial navigation (Wolbers & Hegarty, 2010). Combining the findings from the route and survey learning conditions, we conclude that environmental complexity modulates the transfer of spatial learning: in the aligned environment, both route and survey knowledge develop regardless of which type of spatial knowledge is dominantly used; in the misaligned environment, the type of spatial knowledge that is dominantly used can develop to a high level, but the development of the infrequently used spatial knowledge is very limited.

The results from the pointing task in Experiment 1 showed that survey knowledge was better in the aligned environment than in the misaligned environment regardless of learning conditions. This finding seems to contradict our conclusion that survey knowledge is comparable across environments under the survey learning condition. We explain the apparent contradiction as follows: In our experiments, the penetrable trials measured participants' survey knowledge from familiar locations to other familiar locations (i.e., from one target storefront to another target storefront). The pointing task, on the other hand, measured survey knowledge from a less familiar location to familiar locations (i.e., from the starting location to target storefronts). In the survey learning condition, because participants navigated in a penetrable environment most of the time, their survey knowledge of the familiar locations was acquired directly, regardless of the environmental complexity, which explains the absence of an environmental complexity effect in the penetrable trials. Although the survey knowledge of the familiar locations was acquired directly, this survey knowledge transferred very little to the less familiar locations in the complex environments. Therefore, we observed an environmental complexity effect on the pointing task but not on the penetrable trials. Another possibility is that the penetrable trials and the pointing task measured similar but not identical spatial knowledge. The penetrable trials were compatible with how participants navigated in the environment but the pointing task was not, and this

45

difference in learning-testing compatibility might be the cause of the different pattern of results (Franks et al., 2000; Morris, Bransford, & Franks, 1977). An experiment that had participants point from one target storefront to other target storefronts could be useful to investigate this issue.

In Experiment 2 where participants had rotational body-based information, the pattern of results in the route learning condition was very similar to the one in Experiment 1, further supporting our conclusion that impenetrable and penetrable trials measured different spatial knowledge, and the transfer from route to survey knowledge was very limited in the misaligned environment. The results from the survey learning condition, however, were different from those in Experiment 1. First, performance was better in the aligned environment than in the misaligned environment, in terms of the navigational trials and the pointing task. By comparison, performance in the survey learning condition of Experiment 1 was not better in the aligned environment than in the misaligned environment in terms of penetrable trials. Furthermore, in terms of pointing error, performance in the aligned environment of the survey learning condition in Experiment 2 was better than performance in the other aligned environments (aligned environments in Experiment 1, as well as the aligned environment of Experiment 2 in the route learning condition). These findings imply that rotational body-based information benefited the acquisition of spatial knowledge the most when the environment was regular and people could learn the spatial relationships between locations more directly (i.e., survey learning condition). Second, in the misaligned environment, the patterns of performance in the route and survey learning conditions were very similar in Experiment 2. We speculate that participants in the misaligned environment of the survey learning condition navigated the environment in a way similar to the route learning condition, in which penetration of the buildings was rare. This aversion to building penetration could be due to the combination of environmental complexity and slow speed (e.g., people got lost more easily when they penetrated the buildings, and the slow speed took them a long time to orient in the environment). More research is needed to shed light on this issue.

Due to the speed differences between Experiments 1 and 2, we conducted a control experiment to compare the performance between the Desktop and HMD, under the survey learning condition in the aligned environment. We found that performance in the impenetrable and penetrable trials was significantly better in the HMD than in the Desktop, suggesting that

rotational body-based information played a role in spatial navigation in a large-scale environment. Our finding seems to be in conflict with Ruddle et al.'s (2011) finding, which showed that rotational body-based information did not enhance survey knowledge acquisition, but our paradigms are different from theirs: In our control experiment, participants could penetrate the buildings most of the time. This could render the rotational body-based information more useful, because participants did not need to turn frequently to reach the destination, and it was easier for them to stay oriented with their body-based information. In Ruddle et al.'s (2011) experiment, participants could not penetrate the buildings at all, and frequent turning could make keeping track of the orientation difficult, which in turn downplayed the role of rotational body-based information. Therefore, it seems that the role of rotational body-based information depends on the extent to which it can be relied on to stay oriented.

Previous studies showed that the development of route and survey knowledge could be affected by navigational goals (Taylor et al., 1999) and presentation of the environmental information (Münzer et al., 2012). Our study showed that this developmental pattern could also be affected by the type of spatial information that was relied on in learning an environment. We assume that the route information is better utilized and learned in the route learning condition, and the survey information is better utilized and learned in the survey learning condition. The interaction between learning condition and trial type in Experiment 1 suggests that learning conditions affected the acquisition of spatial knowledge in the misaligned environment. In the aligned environment, however, learning conditions had no influence, suggesting that route and survey knowledge can be transferred to each other. Based on these findings, it is natural to ask the following important questions: 1) what are the underlying mechanisms behind this transfer of spatial knowledge and 2) what determines this transfer.

To determine the underlying mechanisms behind the transfer of spatial knowledge, we need to look at the findings from the brain imaging studies of spatial navigation. If we assume that route knowledge is primarily the output of response learning and survey knowledge is primarily the output of place learning, then we can consider that caudate nucleus is responsible for route knowledge development and hippocampus is responsible for survey knowledge development (Hartley et al., 2003; Iaria et al., 2003; Marchette et al., 2011). Based on our findings, it is plausible to conjecture that the caudate nucleus communicates with the

hippocampus and vice versa during navigation in a regular environment but this communication does not occur or is attenuated in a complex environment. A brain imaging study comparing activation patterns between environments of different complexities could shed light on this issue.

To answer the question about what determines the transfer of spatial knowledge, our results suggest that environmental complexity modulates this transfer. We manipulated the VGA across environments by varying the alignment between the buildings and the boundary, but this is not the only way to manipulate environmental complexity. Space syntax is a set of methods to measure space properties objectively. By applying other methods to manipulate the spatial properties systematically, we can not only investigate what environmental factors affect people's perceived environmental complexity and what facilitates or interrupts people's spatial learning, but also how tightly these factors are correlated (e.g., does perceived complexity completely determine wayfinding efficiency?). This investigation has important real-life implications such as a guide to the infrastructure design of a hospital where finding a place of interest is time-sensitive.

Another way to improve spatial learning is the inclusion of rotational body-based information. Due to the availability of the consumer-level virtual reality headsets in the market, including rotational body-based information in spatial navigation is very affordable. The control experiment of the current study showed that rotational body-based information could enhance navigational performance significantly. However, it seems that being able to penetrate the environment is necessary to enable the effect of rotational body-based information. Although in real-life people can never penetrate objects, this training paradigm could be implemented in a virtual environment and the spatial knowledge gained in the virtual environment could be tested in the real environment (Waller, Hunt, & Knapp, 1998). The better survey knowledge acquired by allowing people to penetrate the objects could enable flexible route planning and help people find a detour faster if the familiar path is blocked. The current project only investigated the role of rotational body-based information, and Ruddle et al. (2011) found that translational body-based information also facilitated survey knowledge acquisition. Further research can investigate whether people can take more advantage of a penetrable environment when they can walk naturally (translation and rotational body-based information combined), and what types of environments could maximize this effect.

One possible limitation of the comparison between the impenetrable and penetrable trials is that although the visual stimuli were very similar between these trials, they differed when people penetrated a building: the building being penetrated disappeared and people could see the buildings on the other side. In this sense, people could see slightly more of the environment in the penetrable trials than in the impenetrable trials. We controlled the presentation in this way to match the visual stimuli between these two types of trials and at the same time to encourage participants to penetrate when it was possible. There are other ways to implement the visual presentation when people are inside of a building; for example the building being penetrated could become translucent so that people could still see that building and the outside at the same time; or everything could become black (like being in a tunnel) when people were inside a building. It remains to be seen how these visual presentations affect people's acquisition of spatial knowledge and their tendency to penetrate the environment.

For individual differences, the various measures predicted a significant but small portion of variance beyond the experimental variables, with a large portion of variance in individual differences left unexplained. This finding confirms the conclusion from Weisberg et al. (2014) that while self-report measures are important, objective methods are needed to further capture the marked individual differences in spatial ability.

Chapter 4

Future Directions

The new type of wayfinding trial and paradigm we developed in this research raise some interesting questions. The first one concerns the transfer of spatial knowledge from well-traveled to less-traveled locations based on the environmental complexity. We conjecture that this transfer only happens in the regular environment, and future research is needed to test this hypothesis as well as the extent of the transfer. In addition, it would be interesting to identify other factors that could also modulate this transfer besides environmental complexity, such as manipulating the allocation of attentional resources by introducing a secondary task or instructing participants to focus on the routes or direct spatial relations. This could be useful to examine the automaticity and other properties of this transfer.

In the current study we were not able to decouple alignment from visibility to investigate which factor made the misaligned environment more complex than the aligned environment. We conjecture that compartmentalization or regionalization might have been the cause of the perceived complexity of the misaligned environment. Because the gaps between the buildings in the misaligned environment were very small (Fig.3, Right), participants might have represented the environment as a number of disconnected local environments (e.g., Meilinger,2008) instead of as a cohesive global environment. On the other hand, the spacing between buildings in the aligned environment was so wide that participants could represent the environment as a whole. This hypothesis could be tested in a factorial design that jointly manipulated alignment and visibility.

There are a few studies investigating the pattern of brain activation during a route-following task vs. a wayfinding task (Hartley et al., 2003; Maguire et al., 1998), and our findings showed that the traditional wayfinding task cannot fully measure the survey knowledge as

previously suggested. Because the visual presentation and stimuli in the penetrable trials are almost identical to the traditional wayfinding task, it would be informative to compare the patterns of brain activation in these two tasks during the early and late stages of spatial learning. This research could let us better understand the neural correlates of the formation and consolidation of the cognitive map.

Finally, we only directly compared the performance between the Desktop and the HMD in one condition (survey learning in an aligned environment) in the control experiment, so more studies are needed to further determine when the rotational body-based information is beneficial and why. This finding could lead us 1) to design a more efficient spatial training paradigm for people whose profession requires them to get to a destination as soon as possible (e.g., ambulance driver), and 2) to better study the mechanisms of how people assign weights to their body-based cues and to visual cues during spatial navigation (Chen et al., 2017).

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This appendix reports the statistical results of the excessive time in Experiments 1, 2 and the control experiment.

Experiment 1

Route Learning Condition

Impenetrable trials. Excessive time was analyzed in a 4 (block) X 3 (environment) mixed-ANOVA (Figure 6). The main effect of blocks was significant ($F(3, 135) = 43.20$, $MSE = 6.88$, $p < .001$, $\eta^2 = .49$), and the main effect of environment was marginally significant ($F(2, 45) = 3.19$, $MSE = 8.34$, $p = .051$, $\eta^2 = .12$). The interaction was not significant ($F(6, 135) = .27$, $MSE = 6.88$, $p = .94$, $\eta^2 = .01$). The linear trend contrast across blocks was significant ($F(1, 45) = 65.80$, $MSE = 10.50$, $p < .001$, $\eta^2 = .59$).

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was not significant ($F(2, 45) = .73$, $MSE = 3.88$, $p = .48$, $\eta^2 = .03$). Planned pairwise comparisons showed that none of the comparisons was significant (ts$(45) < 1.17$, ps$ > .24$).

Penetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted (Figure 6). The main effect of blocks was significant ($F(3, 135) = 12.48$, $MSE = 7.05$, $p < .001$, $\eta^2 = .21$), as well as the main effect of environment ($F(2, 45) = 3.56$, $MSE = 16.65$, $p = .036$, $\eta^2 = .13$). The interaction was not significant ($F(6, 135) = .62$, $MSE = 7.05$, $p = .71$, $\eta^2 = .027$). The linear trend contrast across blocks ($F(1, 45) = 32.64$, $MSE = 7.97$, $p < .001$, $\eta^2 = .42$) and environment ($F(1, 45) = 7.11$, $MSE = 4.16$, $p = .01$, $\eta^2 = .21$) were both significant.

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was marginally significant ($F(2, 45) = 2.73$, $MSE = 4.34$, $p = .076$, $\eta^2 = .11$). Planned pairwise comparisons showed that participants in the aligned environment performed significantly better than those in the misaligned environment ($t(45) = 2.27$, $p = .03$), and no other comparisons were significant (ts$(45) < 1.64$, $p > .11$).

Furthermore, significant improvement between the first and last blocks occurred in all environments (ts(15) > 2.45, ps < .027).

Survey Learning Condition

Penetrable trials. Excessive time of penetrable trials was analyzed in a 4 (block) X 3 (environment) mixed-ANOVA (Figure 7). The main effect of blocks was significant ($F(3, 135)$ = 43.03, MSE = 7.71, p < .001, η^2 = .48), but neither the main effect of environment nor the interaction was significant ($F(2, 45)$ = 1.85, MSE = 14.81, p = .16, η^2 = .07; $F(6, 135)$ = .32, MSE = 7.71, p = .92, η^2 = .01). The linear trend contrast across blocks was significant ($F(1, 45)$ = 107.85, MSE = 8.52, p < .001, η^2 = .70).

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was not significant ($F(2, 45)$ =.58, MSE = 3.44, p = .56, η^2 = .02). None of the planned pairwise comparisons was significant (ts(45) < 1.07 , ps > .29).

Impenetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted. The main effect of blocks was significant ($F(3, 135)$ = 13.36, MSE = 9.59, p < .001, η^2 = .22), as well as the main effect of environment ($F(2, 45)$ = 6.89, MSE = 12.86, p = .002, η^2 = .23). The interaction was not significant ($F(6, 135)$ = .60, MSE = 9.59, p = .72, η^2 = .02). The linear trend contrasts across blocks ($F(1, 45)$ = 22.93, MSE = 13.28, p < .001, η^2 = .33) and environments ($F(1, 45)$ = 8.89, MSE = 3.21, p = .005, η^2 = .26) were both significant.

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was significant ($F(2, 45)$ = 4.49, MSE = 3.26, p = .017, η^2 = .19). Planned pairwise comparisons showed that performance in the aligned environment was significantly better than those in the half-aligned ($t(45)$ = 2.50 , p = .016) and misaligned environments ($t(45)$ = 2.68 , p = .01), but there was no significant difference between the half-aligned and misaligned environments ($t(45)$ = .17 , p = .86). Furthermore, significant improvement between the first and last blocks was observed in all environments (ts(15) > 3.33, ps < .005).

Transfer of Spatial Knowledge

A 2 (learning condition) X 2 (trial type) two-way mixed ANOVA was conducted for each environment. In the aligned environment, the main effects (learning condition: $F(1, 30) = .05$, $MSE = 5.41$, $p = .82$, $\eta^2 = .002$; trial type: $F(1, 30) = 1.03$, $MSE = 2.44$, $p = .31$, $\eta^2 = .03$) were not significant, and the interaction was marginally significant ($F(1, 30) = 3.86$, $MSE = 2.44$, $p = .059$, $\eta^2 = .11$). In the half-aligned environment, the main effects (learning condition: $F(1, 30) = .002$, $MSE = 11.33$, $p = .96$, $\eta^2 < .001$; trial type: $F(1, 30) = .13$, $MSE = 4.24$, $p = .71$, $\eta^2 = .004$) and the interaction ($F(1, 30) = .04$, $MSE = 4.24$, $p = .84$, $\eta^2 = .001$) were not significant. In the misaligned environment, the main effects (learning condition: $F(1, 30) = .35$, $MSE = 2.53$, $p = .55$, $\eta^2 = .01$; trial type: $F(1, 30) = .97$, $MSE = 1.91$, $p = .48$, $\eta^2 = .01$) and the interaction were not significant ($F(1, 30) = 2.39$, $MSE = 1.91$, $p = .13$, $\eta^2 = .07$).

Experiment 2

Route Learning Condition

Impenetrable trials. Excessive time of impenetrable trials was analyzed in a 4 (block) X 3 (environmental) mixed-ANOVA (Figure 10). The main effect of blocks was significant ($F(3, 135) = 77.43$, $MSE = 13.37$, $p < .001$, $\eta^2 = .63$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = .19$, $MSE = 36.04$, $p = .82$, $\eta^2 = .01$; $F(6, 135) = .21$, $MSE = 13.37$, $p = .85$, $\eta^2 = .01$). The linear trend contrast across blocks was significant ($F(1, 45) = 117.30$, $MSE = 22.48$, $p < .001$, $\eta^2 = .72$).

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was not significant ($F(2, 45) = .93$, $MSE = 4.45$, $p = .39$, $\eta^2 = .04$). None of the pairwise comparisons was significant ($ts(45) < 1.29$, $ps > .20$).

Penetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted (Figure 10). The main effect of blocks was significant ($F(3, 135) = 21.88$, $MSE = 12.05$, $p < .001$, $\eta^2 = .32$), but neither the main effect of environment nor the interaction was significant ($F(2, 45) = .44$, $MSE = 27.89$, $p = .64$, $\eta^2 = .02$; $F(6, 135) = .76$, $MSE = 12.05$, $p = .60$, $\eta^2 = .03$). The

linear trend contrast across blocks was significant ($F(1, 45) = 39.45$, $MSE = 16.61$, $p < .001$, $\eta^2 = .46$).

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was marginally significant ($F(2, 45) = 3.06$, $MSE = 8.80$, $p = .057$, $\eta^2 = .13$). Results of pairwise comparisons showed that participants in the aligned environment performed significantly better than those in the misaligned environment ($t(45) = 2.31$, $p = .025$), and no other comparisons were significant (ts$(45) < 1.89$, $p > .06$). Furthermore, significant improvement between the first and last blocks was observed in all environments (ts$(15) > 3.11$, ps $< .007$).

Survey Learning Condition

Penetrable trials. Excessive time in the penetrable trials was analyzed in a 4 (block) X 3 (environment) mixed-ANOVA (Figure 11). The main effect of blocks was significant ($F(3, 135) = 76.90$, $MSE = 15.50$, $p < .001$, $\eta^2 = .63$), as was the main effect of environment ($F(2, 45) = 5.58$, $MSE = 27.65$, $p = .007$, $\eta^2 = .19$), but the interaction was not ($F(6, 135) = .87$, $MSE = 15.50$, $p = .51$, $\eta^2 = .03$). The linear trend contrasts across blocks ($F(1, 45) = 141.90$, $MSE = 22.05$, $p < .001$, $\eta^2 = .75$) and environments ($F(1, 45) = 9.72$, $MSE = 6.91$, $p = .003$, $\eta^2 = .18$) were both significant.

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was significant ($F(2, 45) = 4.28$, $MSE = 9.88$, $p = .02$, $\eta^2 = .15$). Planned pairwise comparisons showed that performance in the aligned environment was better than that in the misaligned environment ($t(45) = 2.92$, $p = .005$), and no other comparisons were significant (ts$(45) < 1.55$, ps $> .12$).

Impenetrable trials. A 4 (block) X 3 (environment) mixed-ANOVA was conducted (Figure 11). The main effect of blocks was significant ($F(3, 135) = 29.89$, $MSE = 7.34$, $p < .001$, $\eta^2 = .39$), as was the main effect of environment ($F(2, 45) = 7.62$, $MSE = 20.09$, $p = .001$, $\eta^2 = .23$), but the interaction was not significant ($F(6, 135) = .76$, $MSE = 7.34$, $p = .59$, $\eta^2 = .03$). The linear trend contrasts across blocks ($F(1, 45) = 54.10$, $MSE = 11.01$, $p < .001$, $\eta^2 = .54$) and environments ($F(1, 45) = 14.68$, $MSE = 5.02$, $p < .001$, $\eta^2 = .22$) were both significant.

A one-way ANOVA was conducted to compare performance in the last block across environments. The effect of environmental complexity was significant ($F(2, 45) = 9.90$, $MSE = 2.55$, $p < .001$, $\eta^2 = .30$). Planned pairwise comparisons showed that performance in the misaligned environment was worse than the other two environments (ts$(45) > 2.55$, ps $< .015$), with no significant difference between the aligned and half-aligned environments ($t(45) = 1.89$, $p = .064$). Furthermore, significant improvement between the first and last blocks was observed in all environments (ts$(15) > 3.39$, ps $< .004$).

Transfer of Spatial Knowledge

A 2 (learning condition) X 2 (trial type) two-way mixed ANOVA was conducted for each environment. In the aligned environment, the main effects (learning condition: $F(1, 30) = .89$, $MSE = 6.59$, $p = .35$, $\eta^2 = .03$; $F(1, 30) = 1.49$, $MSE = 2.07$, $p = .23$, $\eta^2 = .04$) were not significant, but the interaction was significant ($F(1, 30) = 8.08$, $MSE = 2.07$, $p = .008$, $\eta^2 = .21$). Pairwise comparisons showed that in the aligned environment, impenetrable trials performance was better in the survey learning condition than in the route learning condition ($t(30) = 2.59$, $p = .015$), but the penetrable trials performance was comparable between learning conditions ($t(30) = .50$, $p = .82$). In the half-aligned environment, neither the main effects (learning condition: $F(1, 30) = .08$, $MSE = 35.10$, $p = .77$, $\eta^2 = .003$; trial type: $F(1, 30) = 2.81$, $MSE = 13.53$, $p = .10$, $\eta^2 = .08$) nor the interaction ($F(1, 30) = 1.14$, $MSE = 13.53$, $p = .29$, $\eta^2 = .03$) was significant. In the misaligned environment, the main effect of trial type was significant ($F(1, 30) = 15.13$, $MSE = 5.91$, $p = .001$, $\eta^2 = .33$), but the main effect of learning condition was not ($F(1, 30) = 2.56$, $MSE = 11.97$, $p = .12$, $\eta^2 = .08$). The interaction was significant ($F(1, 30) = 5.08$, $MSE = 5.91$, $p = .032$, $\eta^2 = .14$). Pairwise comparisons showed that in the misaligned environment, penetrable trials performance was better in the route learning condition than in the survey learning condition ($t(30) = 2.09$, $p = .045$), but the impenetrable trials performance was comparable between learning conditions ($t(30) = .02$, $p = .98$).

Control Experiment

Penetrable trials. Excessive time was analyzed in a 4 (block) X 2 (interface) mixed-ANOVA (Figure 14). The main effect of blocks was significant ($F(3, 90) = 65.47$, $MSE = .64$, $p < .001$, $\eta^2 = .68$), but the main effect of the interface was not ($F(1, 30) = .001$, $MSE = 2.40$, $p = .98$, $\eta^2 < .001$). The interaction was significant ($F(3, 90) = 4.30$, $MSE = .64$, $p = .007$, $\eta^2 < .12$). Pairwise comparisons showed that the performance in the HMD was worse than the Desktop in the first block ($t(30) = 2.56$, $p = .015$), but was better than the Desktop in the third and fourth blocks ($ts(30) > 2.09$, $ps < .02$). The linear trend contrasts across blocks was significant ($F(1, 30) = 110.47$, $MSE = .75$, $p < .001$, $\eta^2 = .83$).

Impenetrable trials. A 4 (block) X 3 (interface) mixed-ANOVA was conducted (Figure 14). The main effect of blocks was significant ($F(3, 90) = 13.71$, $MSE = .27$, $p < .001$, $\eta^2 = .31$), but the main effect of the interface was not ($F(1, 30) = .68$, $MSE = .43$, $p = .41$, $\eta^2 = .02$). The interaction was not significant ($F(3, 90) = .61$, $MSE = .27$, $p = .60$, $\eta^2 = .02$). The linear trend contrasts across blocks was significant ($F(1, 30) = 50.18$, $MSE = .21$, $p < .001$, $\eta^2 = .62$).

Appendix B: Subset of Sense of Direction and Spatial Representation Scale

This appendix reports the subset of Sense of Direction and Spatial Representation Scale (SDSR) used in this study.

1. Think about the way you orient yourself in different environments around you. Would you describe yourself as a person:
    a. who orients him/herself by remembering routes connecting one place to another?
        Not at all 1 2 3 4 5   Very much
    b. who orients him/herself by looking for well-known landmarks?
        Not at all 1 2 3 4 5   Very much
    c. who tries to create a mental map of the environment?
        Not at all 1 2 3 4 5   Very much

2. Think of an unfamiliar city. Write the name _____

    Now try to classify your representation of the city:

    a. survey representation, that is a map-like representation
        Not at all 1 2 3 4 5   Very much
    b. route representation, based on memorizing routes
        Not at all 1 2 3 4 5   Very much
    c. landmark-centered representation, based on memorizing single salient landmarks (such as monuments, buildings, crossroads, etc.)
        Not at all 1 2 3 4 5   Very much