

2020

Spatial cognitive implications of user interfaces in virtual reality and route guidance

Alex Floyd Lim
Iowa State University

Follow this and additional works at: <https://lib.dr.iastate.edu/etd>

Recommended Citation

Lim, Alex Floyd, "Spatial cognitive implications of user interfaces in virtual reality and route guidance" (2020). *Graduate Theses and Dissertations*. 18169.
<https://lib.dr.iastate.edu/etd/18169>

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

Spatial cognitive implications of user interfaces in virtual reality and route guidance

by

Alex F. Lim

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Co-majors: Psychology (Cognitive Psychology); Human Computer Interaction

Program of Study Committee:
Jonathan Kelly, Major Professor
Shana Carpenter
Michael Dorneich
Stephen Gilbert
Christian Meissner

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2020

Copyright © Alex F. Lim, 2020. All rights reserved.

TABLE OF CONTENTS

	Page
ABSTRACT.....	iii
CHAPTER 1. GENERAL INTRODUCTION	1
Multiple Types of Spatial Knowledge.....	4
Intersection between Spatial Cognition and Technology	7
Perception of Spatial Properties in Virtual Environments.....	9
Locomotion through Large-scale Virtual Environments.....	10
Route Learning Using a Route Guidance System	11
Overview of Experiments	13
CHAPTER 2. EXPERIMENT 1	14
Introduction	14
Method: Experiment 1	28
Results and Discussion: Experiment 1	32
CHAPTER 3. EXPERIMENTS 2 AND 3	38
Introduction	38
Method: Experiment 2.....	52
Results and Discussion: Experiment 2	59
Method: Experiment 3	61
Results and Discussion: Experiment 3	62
Discussion: Experiments 2 and 3.....	66
CHAPTER 4. DISCUSSION AND CONCLUSION	71
REFERENCES	79
APPENDIX IRB APPROVAL MEMO.....	89

ABSTRACT

The relationship between spatial learning and technology is becoming more intimately intertwined. This dissertation explores that relationship with multiple technologies and multiple types of spatial knowledge. With virtual reality, teleporting is commonly used to explore large-scale virtual environments when users are limited by the tracked physical space. Past work has shown that locomotion interfaces such as teleporting have spatial cognitive costs associated with the lack of accompanying self-motion cues for small-to-medium scale movement in virtual environments, but less is known about whether the spatial cognitive costs extend to learning a large-scale virtual environment. Experiment 1 (Chapter 2) evaluates whether rotational self-motion cues teleporting interfaces impact spatial learning for large-scale virtual environments. using two measures of survey learning (an object-to-object pointing task and map drawing task). Results indicate that access to rotational self-motion cues when teleporting led to more accurate survey representations of large-scale virtual environments. Therefore, virtual reality developers should strongly consider the benefits of rotational self-motion cues when creating locomotion interfaces. For Experiments 2 and 3 (Chapter 3), previous work has demonstrated that repeatedly using GPS route guidance reliably diminishes route learning. Memory research has shown that recalling information (i.e., testing) significantly improves retention of that information when compared to restudying the same information. Similarly, memory retrieval of routes during learning may be advantageous for long-term retention compared to following route guidance using a GPS. However, whether such a benefit would occur for route learning is not clear because the benefits of testing have primarily been explored with verbal materials. Experiments 2 and 3 explore whether retrieving routes from memory during learning enhance route knowledge of a large-scale virtual city using a driving simulator compared to learning a route by

repeatedly following GPS route guidance. Results from both experiments demonstrated that there was no difference in performance between testing and repeatedly following route guidance at final test, but further analysis revealed that in the testing condition, a large proportion of errors produced during learning was also repeated at final test. The experiments described here not only expand the current knowledge regarding the intersection of technology and spatial learning, but also underscore the importance of evaluating applications of spatial cognitive theory across a range of applied domains.

CHAPTER 1. GENERAL INTRODUCTION

Spatial knowledge is essential for everyday life. To illustrate, consider the following scenario. Imagine that you have a meetup scheduled with your friend. Before leaving the house, you study turn-by-turn directions for an unfamiliar route to an unfamiliar location. You successfully get halfway to your destination without having to use your GPS device. As you approach a four-way intersection, suddenly your memory of how to get there becomes foggy, and you cannot quite remember whether to continue straight, turn left or right. You could attempt to recall the route from memory, but an incorrect turn could lead to getting lost, causing you to backtrack and be late to meetup with your friend. Or you could instead turn to your smartphone for Google Maps to provide you wayfinding support. What do you do? Considering that scenario, it might be safe to say that the days of being lost are past us. Current GPS navigation systems (e.g., Google Maps, Apple Maps) have become incredibly efficient in providing wayfinding support with features that provide different perspectives (e.g., turn-by-turn directions or north up birds-eye view map). However, reliance on wayfinding support used in the example above may result in poorer route knowledge acquisition (e.g., Ishikawa, Fujiwara, Imai, & Okabe, 2008). How does relying on GPS-based navigation systems for wayfinding impair route learning? If so, are there ways to improve route learning for more efficient navigation?

Consider another scenario. Imagine a tourist is walking through the streets of London and is scheduled to rendezvous with their friend at a local pub for an afternoon pint. However, the tourist is completely lost and approaches you, a born and raised Londoner. The tourist asks you, “I am supposed to meet my friend at this pub, but this is my first time here in London and I think I might be lost. Could you point me in the direction of this pub **points to a handwritten note** I am looking for?” You know exactly where this pub is because you have been there several times

before, so you point directly (or as some say “as the crow flies”) to the unseen pub. You say to the tourist “Aye mate, I reckon that pub, it is about three to four blocks exactly in that direction.” Because you have extensive experience in London, you were able to recall your stored “map” to help this tourist. This task may have relied on a map-like representation stored in memory often referred to as a “cognitive map” or “survey knowledge” (the two terms are used interchangeably in the literature; survey knowledge is preferred here). This survey knowledge allowed you to make flexible inferences about directions and distances of landmarks within the environment that was not associated with a specific route (O’Keefe & Nadel, 1978; Siegel & White, 1975; Tolman, 1948). Access to survey knowledge is central to accomplishing tasks such as taking novel detours or shortcuts or pointing directly to unseen landmarks. It has been suggested that navigators simultaneously acquire route knowledge and survey knowledge during exploration of the environment, although not necessarily at equal rates (Montello, 1998). Examples of taking novel detours on your way home from work, navigating an unfamiliar city, and finding your way in a complex building are central to everyday spatial navigation tasks.

First, I will review the continuous framework for spatial knowledge acquisition, which highlights how people acquire spatial knowledge of routes, directions, distances, and locations to places they experience and integrate these to form a cohesive spatial representation in memory that can be relied on when needed. Next, I will review the ways in which spatial cognitive theory has intersected with applications within human computer interaction (HCI). The literature described will build on understanding the intersection between spatial cognitive theory and applications that involve spatial navigation. Finally, I will introduce three new experiments by describing the potential and known problems with teleporting in virtual reality (VR), and route learning with GPS use.

The ability to physically walk and turn in large-scale virtual environments (VE) using VR head-mounted displays (HMD) is not feasible with limited tracked physical space. Spatial user interfaces such as teleporting allow users to explore large-scale VEs. To teleport, the user aims a laser pointer to indicate the desired location in the VE and is discretely teleported to that location with no accompanying self-motion cues. Experiment 1 (Chapter 2) evaluates the effect of rotational self-motion cues when teleporting on acquiring accurate survey knowledge. Teleporting interfaces are commonly used in VR video games, but no research to date has directly evaluated the influence of teleporting interfaces on survey knowledge acquisition in large-scale VEs.

Mobile-based GPS applications (e.g., Google Maps) are widely used and provide efficient wayfinding support for navigating from place to place on foot or by car. However, following route guidance reduces the need to retrieve routes from memory and provides an impoverished understanding of the environment, thus leading to poorer route knowledge. Memory retrieval (i.e., testing) benefits retention (see Rowland, 2014 for meta-analytic review), although research has focused primarily on memory for verbal materials (e.g., word lists, reading passages, foreign vocabulary). The benefits of testing could have implications for spatial learning, but little research has been done to examine the testing effect in domains outside of verbal materials. Using a driving simulator task, Experiments 2 and 3 (Chapter 3) evaluate whether memory retrieval for routes leads to better route knowledge compared to repeatedly following route guidance.

The review of literature and experiments presented here highlights not only the need to understand how humans acquire different spatial properties to form accurate survey and route

knowledge, but it also underscores the importance of understanding the intersection between technology and spatial learning to be applied in various real-world contexts.

Multiple Types of Spatial Knowledge

The ability to find our way between places in large-scale environments is essential for effective functioning in everyday life. Becoming lost in the modern world is not typically a fatal mistake, but for our ancestors, their very survival depended on successful navigation. This becomes especially important today across many domains that rely on spatial knowledge to perform various tasks, from everyday navigation such as driving to and from work, to urban planners, search-and-rescue teams, pilots, and cartographers. Humans can acquire spatial representations directly through experience in the environment or indirectly through sources such as maps or verbal descriptions (Montello, 1998; Shelton & McNamara, 2004).

Early descriptions of spatial learning described multiple stages (Siegel & White, 1975), where experience within the environment enabled the navigator to progress from one stage to the next in a hierarchical stage-like fashion. According to this view, landmark knowledge is a prerequisite for development of route knowledge, which in turn is a prerequisite for development of survey knowledge. In contrast to the stage-like theory, Montello (1998) posits that individuals continuously learn multiple spatial properties (i.e., landmark knowledge, route knowledge, and survey knowledge) as soon as the individual begins to explore an environment, without the need to pass from one stage to another. This theory suggests that the acquisition of multiple types of spatial knowledge is less stage-like and more continuous.

Landmark knowledge is defined as memory for objects (landmarks) or scenes in an environment (Montello, 1998). Landmark knowledge is central to recognizing self-location (e.g., “I recognize that café so I must be on Main St.”), although it does not, by itself, enable navigation to other known locations. Landmarks serve as visual cues for navigators and can be

categorized as *structural landmarks*, which are geometric features of a layout (e.g., T-junctions or dead-ends), and *object landmarks*, which are specific objects in the environment (e.g., sculptures in a hallway, chair in a room) (Stankiewicz & Kalia, 2007). In general, landmarks can be useful for navigators who are lost or need to reorient themselves while traveling (Nardini, Jones, Bedford, & Braddick, 2008). Or they can be used to link together familiar paths for the purpose of supporting route knowledge (e.g., “I remember that *gas station* on this intersection, turn right here.”).

Route knowledge refers to a prescribed path stored in memory that enables one to travel from one place to another by following a sequence of landmark associations (e.g., turn left when you reach the sculptures) (Montello, 1998). Route knowledge can be considered as a series of actions to be performed at various decision points and is considered to be a form of procedural knowledge (Golledge, 1991). Although route learning is usually a series of landmark-action associations, it can also include representations based on elapsed time or traveled distance. For example, route learning can even occur simply by walking through an environment devoid of landmarks cues. For example, a route could involve walking straight 20 feet (or two blocks, etc.), turn right, walk another 20 feet, turn left, and walk another 10 feet. After some experience with a route, you could likely retrace the route back to the starting location, or even point directly back to the starting location. Though such actions are not without error, they indicate that you have also begun to acquire some level survey knowledge (Ishikawa & Montello, 2006; Montello, 1998; Montello & Pick, 1993).

Survey knowledge (i.e., a cognitive map) is a more complex form of spatial knowledge that can be considered as a map-like representation stored in memory. Acquisition of survey knowledge can either be done through extensive experience navigating in an environment or

through studying a map (Siegel & White, 1975; Wolbers & Büchel, 2005). Although the term “cognitive map” is convenient for describing survey knowledge, it also suggests that survey knowledge is map-like. In fact, spatial cognitive research indicates that it is not so map-like because spatial memories of experienced environments are orientation specific (Shelton & McNamara, 2001), are subject to various distortions and biases (Tversky, 1981), and do not adhere to Euclidean properties of space (McNamara & Diwadkar, 1997) (e.g., judged distance from A to B is not necessarily the same as B to A). In one experiment (Shelton & McNamara, 2001), participants viewed a spatial array of objects placed on a rectangular rug that was oriented to be congruent with the room from two views, one from 0 degrees (aligned view) and another from 135 degrees (misaligned view) with respect to the rug. Then participants performed a series of judgments of relative direction (JRD) pointing tasks which requires memory retrieval from various imagined perspectives (“Imagine standing at the book, facing the clock. Point to the lamp.”). Regardless which view the participants experienced first, memory for the objects was best at 0 degrees in the aligned view which likely explains a preference in adopting an experienced view that was salient to an axis aligning with the environment. Other evidence has also shown that humans tend to make errors around reference frames. Tversky (1981) found that map drawings of familiar areas were prone to systematic errors and distortions, thereby demonstrating that people tend to want their environments to adhere to rectangular properties. For example, participants aligned intersecting roads at 90 degrees despite the roads deviating at 60 degrees and 115 degrees, respectively. Although survey knowledge is not perfectly map-like, it does enable one to construct novel routes or point to unseen locations from experienced environments (e.g., standing in front of Howe Hall and pointing directly to Lagomarcino Hall).

Montello's (1998) *continuous framework* posits that with little exposure to an environment, an individual develops all three types of spatial knowledge (landmark, route, and survey knowledge) as soon as they begin exploring an environment, acquiring spatial knowledge about distances and directions at different rates (e.g., Montello & Pick, 1993). Though route and survey knowledge develop simultaneously, neuroimaging studies have also confirmed their distinctions which suggest that survey knowledge is associated with the hippocampus while route knowledge is associated with the caudate nucleus (Hartley, Maguire, Spiers, & Burgess, 2003).

Not only do these spatial properties accumulate simultaneously at different rates as soon as the navigator begins exploring an environment, but spatial knowledge continues to develop indefinitely as familiarity and exposure increase within that space, thus becoming more precise over time. For people with lower spatial ability (e.g., older adults), survey knowledge may take longer to develop, suggesting that individual differences may also contribute to varying rates of survey knowledge acquisition (Carlson, Hölscher, Shipley, & Dalton, 2010; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Ishikawa & Montello, 2005; Montello, 1998).

Intersection between Spatial Cognition and Technology

The virtual reality (VR) market is a growing billion-dollar industry with millions of VR units (e.g., Playstation VR, Oculus Quest, and HTC Vive) sold worldwide, and this trend is expected to increase over the next several years (Liu, 2019; Forbes, 2019). VR has proven to be a useful tool in education, industry, and entertainment (Mainelli, Shirer, & Ubrani, 2019). Using both immersive VR head-mounted displays (HMD) and desktop VR in laboratory research enables the possibility to further understand how humans perceive, remember, and navigate through large-scale spaces in ecologically valid contexts, with a high degree of control and standardization. Applications of VR HMDs and mobile device applications (e.g., Google Maps) could be seen as useful tools for spatial learning. Consider a navigator who is lost in a strange

city, they could rely on using mobile-based GPS applications to pull up a birds-eye view map or rely on turn-by-turn route guidance. These tools may be especially helpful for older adults who often experience serious problems with spatial navigation tasks who may require navigational aids (Diersch, & Wolbers, 2019; Lester, Moffat, Wiener, Barnes, & Wolbers, 2017). In another example, the use of augmented reality (AR) can be accomplished using current smartphone technology which allows for creating an interactive experience where objects in the real-world are enhanced by computer-generated perceptual information and displayed on the device to the user. For example, Google Maps AR is a mobile-based application which provides users the ability to scan their surroundings using the camera on their mobile device and the application superimposes orienting directions over the real-world, thus providing another layer of wayfinding support.

Consumer VR HMD systems (e.g., Oculus Quest, HTC Vive) allow gamers to experience rich immersive VEs that Recent advancements in VR have grown considerably, providing users a plethora of VR technologies and immersive experiences in VEs. Consumer VR HMDs have become more affordable (e.g., HTC Vive, Oculus Quest), offering flexible forms of experiences with full interactive movement in immersive VEs across a variety of domains, increasing levels of presence which is a cognitive state of being “immersed” and increased levels of enjoyment (see Chirico, Yaden, Riva, & Gaggioli, 2016). In addition to consumer entertainment, VR HMDs have been evaluated in place of current navigation training methods for firefighters, astronauts, and the military (Aoki, Oman, & Natapoff, 2007; Bliss, Tidwell, & Guest, 1997), or as a diagnostic tool for detecting Alzheimer’s disease (Cushman, Stein, & Duffy, 2008; Montenegro, & Argyriou, 2017; Serino, Morganti, Di Stefano, & Riva, 2015).

Despite these benefits, there are also several shortcomings of these tools, which can negatively impact spatial cognitive functions as well as user experience. Therefore, it is important to evaluate and understand how these technologies interact and permeate through our everyday life. In this section, three specific spatial cognitive challenges associated with VR and GPS route guidance are reviewed: perception of spatial properties of virtual environments, locomotion through virtual environments, and route learning when following a route guidance system.

Perception of Spatial Properties in Virtual Environments

There are anecdotes of individuals who express feelings of awe when they put on an HMD and experience VR for the first time. VR designers have continually raised the bar in creating VR experiences that are rich and immersive, “transporting” users to futuristic landscapes, walking on the surface of Mars, or geological field-trips to locations that are not readily accessible. The experience of awe can depend on the perception of vastness and large visual space that some VR experiences present. For example, staring out across a Martian landscape or a deep mountain forest can remind us that we are small compared to the rest of the universe. Studies that have investigated *vastness* have found that these large-scale immersive spaces in VR that evoke a sense of awe influence distance estimates and perceived sense of smallness (Rauhoeft, Leyrer, Thompson, Stefanucci, Klatzky, & Mohler, 2015). Similarly, others have found higher ratings of subjective presence which in turn can induce more reflexive behaviors from individuals that resemble real-world circumstances (for review see Chirico, Yaden, Riva, & Gaggioli, 2016). Implications of this research suggest that VR is a promising tool for both in research and in application for spatial cognitive researchers to study how humans acquire spatial properties that closely resemble real-world contexts.

Spatial experiences such as vastness depend on perception of 3D space. More directly to the point of this dissertation, accurate survey knowledge also requires accurate perception of the environment. Humans are well calibrated to the natural world, judging distances to be approximately 100% of the actual distance (Loomis & Knapp, 2004). Distance perception is vital for judging absolute (self-to-object) distances as well as relative (object-to-object) distances. For example, braking at an appropriate distance behind a vehicle, throwing a ball to a friend, or estimating how far away a vehicle is to safely cross the road all hinge on accurate perception of distance. For VR to be effective and ecologically valid requires that VR systems accurately represent the intended environment. However, distances in VR HMDs are often underperceived, and this can be problematic for a wide range of human actions such as walking to fully explore a VE or conducting navigation training in VR (Kelly, Cherep, & Siegel, 2017; Plumert, Kearney, & Cremer, 2005). A review of the literature in 2013 (Renner Velichkovsky, & Helmert) reported that distances in VR are perceived to be approximately 75% of the intended distance. A more recent study (Kelly, Cherep, & Siegel, 2017) found that perceived distance in newer VR HMDs (e.g., HTC Vive) was much more accurate than in older HMDs, and no different than real-world perception, suggesting that newer technology is beginning to resolve the problem, although the mechanism for this improvement is unknown. These results are encouraging for applications of VR HMDs, but there is still room for improvement.

Locomotion through Large-scale Virtual Environments

VR HMDs make it possible for users to physically walk to interact with immersive VEs, with access to all body-based and visual self-motion cues. But due to limited physical tracked space, large-scale VEs cannot be explored through walking. Some locomotion interfaces for exploring large-scale VEs can be accomplished using a joystick or gamepad with smooth visual self-motion and no accompanying body-based cues this often causes cybersickness for users

which creates an undesirable user experience for many. Alternative locomotion methods such as teleporting (sometimes referred to jumping) is a popular spatial user interface for exploring large VEs. To teleport, the user points a virtual laser at the intended location in the VE and is then discretely teleported to that location without any accompanying visual self-motion or body-based cues normally associated with walking. Although teleporting does reduce symptoms of cybersickness compared to joystick navigation (Christou & Aristidou, 2017; Loup & Loup-Escande, 2019), one shortcoming is that the lack of self-motion cues associated with teleporting can cause disorientation for small-to-medium scale movement (Cherep et al., 2020; Kelly et al., 2020).

Past work on the role of body-based cues has shown that rotational self-motion cues associated with rotating one's body are sufficient for keeping track of one's self-location (Klatzky et al., 1998) while other work (Ruddle & Lessels, 2006) has shown that all body-based cues (i.e., translational and rotational) are required to efficiently keep track of one's movement through space in a foraging task. This is problematic because many locomotion interfaces for VR vary in access to these body-based cues and depending on the navigation goal, the spatial cognitive consequences associated with these locomotion interfaces are not well understood. Therefore, it is important from an applied perspective to empirically evaluate and understand these shortcomings.

Route Learning Using a Route Guidance System

GPS devices have long provided navigators with wayfinding support through turn-by-turn directions from a first-person perspective (e.g., Google Street View) or a birds-eye view map. From a user experience perspective, navigators now can rely on GPS technologies (e.g., Google Maps) to provide turn-by-turn wayfinding support for unfamiliar routes which can be a positive experience and beneficial for some like older adults who may suffer from spatial

navigation problems. Such technologies also reduce the need to store and retrieve routes from memory, and can be considered as a form of cognitive offloading (Risko & Gilbert, 2016). But do such devices have spatial cognitive costs? Recent studies have demonstrated that GPS devices as navigational aids can negatively impact spatial learning (Fenech, Drews, & Bakdash, 2010; Gardony, Brunyé, Mahoney, & Taylor, 2013; Hejtmánek et al., 2018). Some of the proposed reasons for the negative impact of GPS on spatial learning suggest that navigators who use GPS may pay more attention to the device than their surroundings (Hejtmánek et al., 2018), have difficulty learning due to divided attention (Gardony et al., 2013), or do not encode environments into spatial working memory (Münzer et al., 2006).

Although laboratory studies have explored spatial cognitive costs associated with GPS use, there are still unexplored mechanisms associated with these costs. For example, everyday navigation (e.g., driving home to and from work) is likely to resemble what London bus drivers accomplish by repeatedly taking the same predefined routes, unlike London taxi drivers who require extensive training, committing thousands of routes and landmarks to memory, and they are not allowed to use a GPS in their line of work (Maguire, Woollett, & Spiers, 2006).

Similarly, GPS mobile-based applications reduce the need to rely on memory retrieval for spatial knowledge. However, memory research would suggest that the effort in retrieving routes from memory could enhance long-term retention of spatial knowledge in the same way research on testing has benefited learning for verbal materials (for review see Kornell & Vaughn, 2016). Testing has shown significant benefits to learning and such an intervention could be applied to domains outside of verbal materials. The examples of intersections between spatial cognitive research and HCI applications reviewed here highlights the importance that different experiences and interactions with prevailing technologies can impact spatial cognitive processes.

Overview of Experiments

Virtual environments are inherently spatial, and spatial user interfaces are required in order to interact with them. Therefore, it is important to examine the impact of spatial user interfaces on spatial learning. To that end, Chapter 2 (Experiment 1) presents an experiment evaluating two variations of a commonly used locomotion interface in VR called teleporting. Locomotion interfaces in VR vary in the availability of self-motion cues, which are vital for keeping track of one's self-location (Cherep et al., 2020; Kelly et al., 2020). However, it is unclear whether manipulating access to self-motion cues affects the accuracy of acquired survey knowledge (i.e., cognitive map). To test this, the reported experiment compares two forms of teleporting: one with rotational self-motion cues and one without. The results have implications for both virtual reality applications and spatial cognitive theory.

For GPS devices, there is a plethora of research suggesting that relying on them as a navigational aid can impair route learning. On the other hand, navigational aids are incredibly helpful tools. In order to mitigate the consequences of following GPS route guidance, we must understand the underlying problem. Chapter 3 (Experiments 2 & 3) explores the possibility that GPS route guidance impairs route learning by reducing the need for memory retrieval. This potential explanation follows research on the testing effect, whereby retrieval of previously learned information enhances long-term retention of that information. Two experiments explore the effect of route testing on route learning in a driving simulator. Testing has been shown to benefit learning verbal materials (e.g., word pairs, reading passages, etc.), but it is unknown whether testing enhances acquisition of route knowledge.

CHAPTER 2. EXPERIMENT 1

Implications of teleporting in virtual reality and acquisition of survey knowledge

Introduction

A key feature of VR is the ability to explore virtual environments (VEs) by physically walking to translate (i.e., change position) and turning to rotate (i.e., change orientation) in the VE. However, this experience in VR is often limited by the walkable tracked space available (e.g., office, living room, etc.), and therefore problematic for traveling longer distances across larger VEs. Physical space restriction requires alternative modes of locomotion in VEs, and to accomplish this through methods that feel natural to the user has been a significant challenge for VR locomotion research. One popular method of locomotion in VR is teleporting (or sometimes referred to as “jumping”), whereby the user points to a location in the VE and is discretely teleported to that location, typically without any accompanying self-motion cues. Teleporting as a method of locomotion is commonly used for traveling across a myriad of large VEs, but uses of this method are typically found in VR video games (Zayer, MacNeilage, & Folmer, 2018). Advantages of using the teleporting interface are that it is easy to use and reduces cybersickness (e.g., Christou & Aristidou, 2017) that is often experienced when using a gamepad or joystick to translate through a VE which often creates an undesirable experience for users. On the other hand, there are disadvantages with teleporting interfaces that primarily stem from the lack of body-based cues associated with real walking which is vital for spatial updating (i.e., the process of mentally tracking one’s self-location and self-orientation during locomotion).

There is strong evidence that self-motion cues are critical for successful navigation (e.g., Klatzky et al. 1998; Ruddle & Lessels, 2006) and that there are spatial cognitive costs with using teleporting interfaces (e.g., Cherep et al. 2020; Kelly et al., 2020) that lack self-motion cues

because it can often lead to being disoriented. Expanding on prior research, the key contributions are to evaluate whether teleporting interfaces (i.e., with rotational and without rotational self-motion cues) impact cognitive map formation, herein referred to as survey knowledge acquisition. Whereas past research has primarily focused on spatial updating, this study contributes important data to evaluate whether the theory (Wang, 2016) that spatial updating is central to accurate acquisition of survey knowledge when navigating large-scale VEs.

Concordance framework for describing locomotion interfaces

Walking and turning one's body is the most natural way to explore VEs. When walking in VR, movement through a VE is **concordant** with movement of the body (Figure 1). Within this concordance framework (Cherep et al., 2020) natural walking provides all self-motion cues such as proprioceptive cues, vestibular cues, and efferent motor commands (idiothetic information) that are essential for spatial updating. However, VEs often exceed the limited tracked physical space and therefore require different VR locomotion interfaces to overcome this limitation. Because locomotion interfaces are designed to separate the user's movement through the virtual environment from their movement through the real environment, these locomotion interfaces often compromise the concordance between movement through the VE and movement of the body. This section highlights several commonly used methods of locomotion in VR defined within this concordance framework.

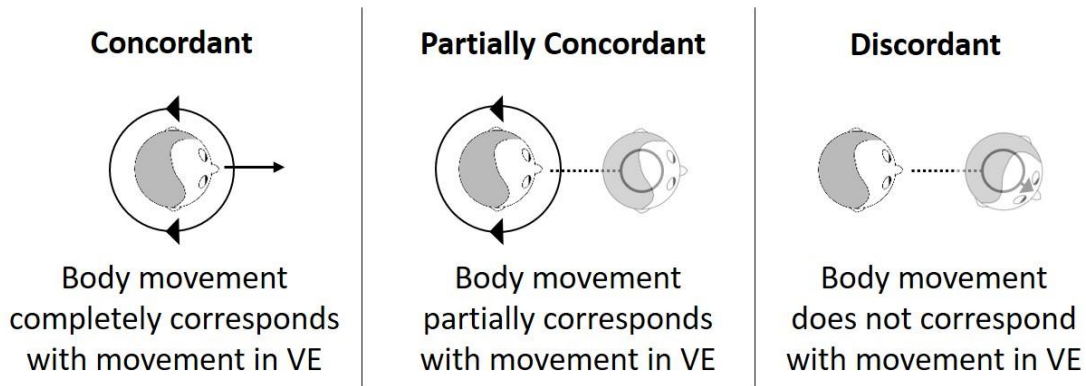


Figure 1. With this concordance framework, locomotion interfaces are categorized based on the extent to which movement of the user's body corresponds to movement in the virtual environment (VE). Each panel provides an example illustration of three interfaces (left panel: user physically rotates and translates to move through the VE; middle panel: user physically rotates but teleports to translate; right panel: user teleports to translate and rotate).

Teleporting is a relatively new, but commonly used locomotion interface for navigating large VEs. One common implementation of the teleporting interface in VR is where the user physically rotates their body to turn in the VE but teleports to translate. In this case, rotations include all body-based and visual self-motion cues that normally occur when rotating in the real world, but translation includes none of the self-motion cues that normally occur when translating in the real world. Within the concordance framework, this teleporting interface is defined as **partially concordant** because rotational movement through the VE is concordant with rotating the body, but translational movement is discordant with movement of the body. Partially concordant teleporting is often used in VR games such as The Lab by Valve or Doom VFR by Bethesda Softworks to travel large VEs (Figure 2).



Figure 2. Example of a teleporting interface commonly used in VR video games. Partially concordant teleporting used in *The Lab* (Valve) demonstrates how the user can indicate where they want to teleport and change position, and to turn in the VE, the user physically rotates their body to change their orientation.

Other partially concordant interfaces have also been developed such as redirected walking, allowing real walking to occur in impossible or limited spaces. For example, applying visual manipulations through small rotational gains (i.e., below threshold of detection) to the user in the VR head-mounted display (HMD) can eventually steer the user away from boundaries of the physical space (Hodgson, Bachmann, & Waller, 2011). Other examples use more discreet redirection, such as when the user reaches a boundary of the physical space and is prompted to “reset” their orientation and/or position before continuing to navigate in the VE. However, resetting can make for an undesirable user experience in VR. Other redirection techniques have leveraged change blindness (Simons & Levin, 1997) to explore large VEs through overlapping virtual spaces by moving doors when the user is looking elsewhere to exploit the same real-world space for different virtual rooms (Suma, Clark, Finkelstein, Wartell, Krum, & Bolas, 2011). Despite all idiothetic information being available to the user, visual manipulations with redirection techniques are not quite consistent with movement of the body, and therefore it is unclear whether these methods support self-localization in the same way that natural walking provides.

Recent advancements in hardware such as omni-directional treadmills (e.g., CyberWalk, Souman et al., 2008) have been developed to simulate natural walking for the same purposes of exploring large VEs. In these versions of partially concordant interfaces, the user is harnessed in at the waist on the treadmill to keep the user stable and close to the center while wearing the HMD. To translate forward in the VE, the user simulates a natural walking gait fixed at the center of the treadmill that is seemingly concordant with movement of the body if translational gains in the VE are appropriately tuned and if movement of the head and rate of turning is concordant with movement of the body. While the hardware seems promising for creating realistic user experiences for methods of traveling in VR, there is very little spatial cognitive research (e.g., Souman et al., 2008) on whether these treadmills produce a level of fidelity that closely resembles real walking, but lacks acceleration cues from the inner ear which is likely to produce some discordance. Omni-directional treadmills may one day find their way into homes of everyday VR consumers, but until then, the costs and physical space required to own one is not likely reasonable for the average VR consumer. Walking-in-place is another (Templeman, Denbrook, & Sibert, 1999) partially concordant interface akin to omni-directional treadmills that simulates a walking gait whereby the user marches in place and steps are converted to equal (or larger) translational gains in the VE and rotational self-motion cues associated with turning of the body are concordant with rotations in the VE. Partially concordant interfaces are popular in a variety of VR applications, but it is unclear what impact they have when learning large-scale VEs.

Discordant teleporting (e.g., Robo Recall by Epic Games) is another, less common locomotion interface that requires the user to teleport to translate and rotate with no associated body movement. To rotate and translate, the user positions and orients a marker (e.g., an arrow)

on the ground plane and is then teleported to that location and orientation. Advantages of discordant teleporting interface include accessibility that is necessary for users who have limited or impaired mobility that prevent them from using concordant or partially concordant locomotion interfaces. In-flight entertainment is another example in which discordant teleporting would be helpful when body movement is restricted. Within the concordance framework, movement through the VE is **discordant** with movement of the body. Discordant teleporting is undesirable because it removes translational and rotational self-motion cues that are critical for spatial updating (e.g., Cherep et al., 2020, Kelly et al., 2020). Other similar discordant interfaces have been developed such as gaze directed steering (GDS) which allows the user to steer through the VE based on the direction of their gaze, but this prevents users from looking around while moving because the gaze direction is coupled with their steering direction (Bowman, Koller, & Hodges, 1997). Other similar methods such as hand-directed steering (HDS) allows the user to control the direction and speed of travel based on the direction and length vector between their hands (Bowman, Wingrave, & Campbell, 2001). Evaluations comparing HDS and GDS methods have been met with mixed results with one method favoring the other depending on the demands and goals of the navigation task (e.g., Bowman et al., 1997; Suma et al., 2009). Joystick or other gamepad control devices have been employed for smooth visual movement to translate through the VE without self-motion cues other than optic flow. However, these methods often cause cybersickness with users (e.g., Christou & Aristidou, 2017) because of the mismatch between visual and body-based self-motion cues. Despite the drawbacks of many discordant locomotion methods such as teleporting, they have become a popular choice for traveling large distances in VEs with minimal effort (Bozgeyikli, Raji, Katkoori, & Dubey, 2016; Langbehn, Lubos, & Steinicke, 2018) and the reduced likelihood of cybersickness compared with other interfaces that

include visual self-motion (Christou & Aristidou, 2017; Moghadam, Banigan, & Ragan, 2018; Langbehn et al., 2018; Weißker, Kunert, Fröhlich, & Kulik, 2018). That said, there is a spatial cognitive cost associated with the lack of self-motion cues when using a teleporting interface which is critical for spatial updating because the lack of self-motion cues is likely to cause disorientation which indicates a failure in spatial updating.

Spatial cognitive researchers have been working towards developing feasible locomotion methods with attempts to understand the spatial cognitive implications (e.g., Cherep et al., 2020; Kelly et al., 2020) of teleporting in VR, but there is very little known with regard to the spatial cognitive costs associated with these teleporting methods when navigating and learning large VEs and their impact on survey knowledge acquisition.

Spatial cognitive research on self-motion cues for spatial updating

The general consensus is that self-motion cues are critical for spatial updating. Internal self-motion cues (i.e., idiothetic information) include vestibular stimulation, proprioception, and efference copies of motor commands. External self-motion cues are provided by optic flow and acoustic flow that occur during self-motion. What is unclear in the research is the precise individual contributions of these self-motion cues which could be attributed to differences in the demands of the navigation task (e.g., Klatzky et al., 1998; Ruddle & Lessels, 2006). However, spatial updating research points to a particularly important role for internal self-motion cues (Chance, Gaunet, Beall, & Loomis, 1998; Grant & Magee, 1998; Ruddle, Volkova, & Bühlhoff, 2011; Ruddle, Volkova, Mohler, & Bühlhoff, 2011; Waller, Loomis, & Haun, 2004).

In spatial cognitive research, triangle completion is a commonly used spatial updating task. The participant travels two straight legs of an outbound path separated by a turn, and at the end of the outbound path, the participant points to or returns directly back to the starting location.

In a seminal study using triangle completion, participants wore a VR head-mounted display (HMD) and were placed in an impoverished VE with no orienting landmark cues. Errors were greatest when movement along the outbound path was only visual, and errors were smallest when participants had all self-motion cues (walked and turned) or when they had all rotational self-motion cues but only visual (and not body-based) translational cues (Klatzky et al., 1998). In a similar study (Ruddle & Lessels, 2006) evaluating the contribution of body-based cues, participants performed a foraging task using immersive VR that required participants to search for targets hidden in boxes scattered throughout a small-scale VE, and access to body-based self-motion cues was manipulated (real walking, rotational self-motion cues and using a joystick to translate, and vision only using a joystick to rotate and turn). The dependent measure used was the number of times a box was checked more than once, indicating a failure in spatial updating. Performance on this task was best when participants walked and turned during the search task, but rotational self-motion cues and vision only were equally worse than the real walking condition. Results from this suggest that translational and rotational self-motion cues are required for successfully completing a navigational search task. The demands of the two tasks (i.e., triangle completion and foraging task) might explain whether differences are attributed to translational cues or rotational cues. It is possible that a foraging task requires all body-based cues associated with full walking, and the triangle completion task only requires rotational cues.

In a series of five experiments (Cherep et al., 2020), researchers measured triangle completion performance with three locomotion interfaces: walking, partially concordant teleporting, and discordant teleporting. The availability of environmental cues, such as landmarks and geometric boundaries (room walls or a fence), was also manipulated. Across all experiments, discordant teleporting was found to consistently produce larger triangle completion

errors than partially concordant teleporting which produced larger errors than walking. Surprisingly, landmarks alone were unhelpful for reorienting when using the teleporting interfaces, but landmarks and boundaries together act as piloting cues that are helpful in mitigating errors associated with varying degrees of discordance. In another study (Kelly et al., 2020), the influence of rotational self-motion cues when teleporting on spatial updating performance was evaluated across small-and-large scale movement in two VEs that varied in environmental scale. Participants performed a triangle completion task using two teleporting interfaces and access to rotational self-motion cues were manipulated. Overall errors across all levels of movement scale and environmental scale were reduced when using partially concordant teleporting, and this was exaggerated when navigating large triangles and when the surrounding VE was small, bringing participants closer to surrounding landmarks and boundaries which led to greater reliance on piloting (i.e., landmark-based navigation). Evidence from these studies not only reflects the importance of body-based self-motion cues needed for spatial updating, but also the contributions of orienting boundaries and landmarks in reducing spatial disorientation when teleporting interfaces are used.

Spatial cognitive research on survey knowledge acquisition

Acquisition of survey knowledge can either be done through extensive experience navigating in an environment through path integration or learning a map (Siegel & White, 1975; Wolbers & Büchel, 2005). Early evidence of survey knowledge was originally discovered in rats. Tolman (1948) demonstrated that rats can execute flexible navigational behaviors such as taking shortcuts and proposed that all mobile organisms navigate using survey representations. Whether all organisms possess survey representations is unclear, but it is generally agreed upon that these

spatial representations contain metric information about large-scale environments, which can be used to generate novel shortcuts or to take detours.

To measure and assess survey knowledge, pointing tasks and map drawing tasks are commonly used methods in behavioral studies. For pointing tasks, judgments of relative direction (JRD) task or scene-dependent orientation-dependent perceptual (SOP) pointing task provide a measure of relative directions, while map drawing tasks provide a measure of both relative directions and distances (Huffman & Ekstrom, 2019a; Mackay, 1976; Waller & Hodgson, 2006). In JRD tasks, participants are asked to recall a space and imagine standing at a location of one object and facing a second object, and then point to a third object from that imagined perspective, regardless of their current egocentric position and heading. For example, a JRD trial testing locations on Iowa State campus would be: “Imagine standing in front of Beardshear Hall, facing the Memorial Union. Point to Howe Hall.” While the JRD task relies on imaging the space, the SOP pointing task is primarily dependent on the person being oriented in the environment based on the perceptual details of the scene (similar to the real-world example of providing directions to a stranger). Participants are placed at the location of one object (i.e., they see the visual environment from fixed locations and are free to turn to look in any direction) and are instructed to point in the direction of another learned object. For example, in a SOP pointing task using locations on campus, where the participant is physically standing in front of Beardshear Hall: “You are standing in front of Beardshear Hall. Please point to Howe Hall.” Performance on JRD tasks and SOP pointing tasks are measured using absolute pointing error (in degrees) and either pointing task is suitable for measuring survey knowledge (Zhang, Copara, & Ekstrom, 2012). Survey knowledge in this experiment was assessed using the SOP pointing task.

Map drawings are another way to measure survey knowledge. Using paper and pencil, the participant is instructed to draw a map that indicates the relative position and the inter-relationship of objects to each other. There are a few methods to assess map drawing performance, some studies have employed qualitative approaches by defining a rubric or a set of parameters to follow and graded double-blind by one or more raters (Chrastil & Warren, 2013, 2015). However, methods like this are likely to introduce inconsistencies in scoring of sketch maps as each study differs in their goals, placing emphasis on other aspects of sketch maps such as pathways and buildings that are outside the interest of positions of landmarks. Others have gravitated towards a quantitative approach using bidimensional regression (BDR) to analyze sketch maps (Friedman & Kohlman, 2003). The advantage with using BDR allows for comparing the resemblance of a sketch map's configuration of objects and the target map through correlations between a set of independent X-Y points that are the correct locations of all objects in the target map and a set of dependent A-B points that are the participant's placement of all objects in their sketch map. Once a sketch map is analyzed, an r correlation coefficient is produced and is then converted to R^2 value which reports the variance explained in the participant's sketch map by the actual layout of objects in the true target map. In the present research, map drawings will be scored using BDR with the Gardony Map Drawing Analyzer software (Gardony, Taylor, & Brunyé, 2015).

There is wide agreement that humans possess survey knowledge (see Warren, Rothman, Schnapp, & Ericson, 2017), which is typically acquired through direct experience in the environment or through studying a map. Survey knowledge of small spaces, visible from a single vantage point (i.e., vista spaces), can be acquired through visual scanning and studying of the surrounding environment. Larger spaces, which cannot be viewed in their entirety from a single

vantage point (i.e., environmental spaces), require locomotion in order to learn the environment (Montello, 1993). Spatial updating (reviewed above) during locomotion is thought to play a critical role in linking together survey knowledge from multiple vista spaces into a single representation of the larger environmental space (Montello & Pick, 1993; Richardson, Montello, & Hegarty, 1999). One theory (Wang, 2016) goes even farther to claim that spatial updating is the primary input into survey knowledge acquisition, for both vista and environmental scales of space. Although spatial updating is error prone for all but the shortest travel distances, the theory is that remembered visual scenes are used to reset accumulated error in the spatial updating system.

Given the theorized role of spatial updating in survey knowledge acquisition, one would expect that manipulations that negatively impact spatial updating (e.g., removal of body-based self-motion cues) would also negatively impact survey knowledge acquisition. However, there is disagreement in the literature on this topic, with some studies finding that body-based cues during learning facilitate survey knowledge acquisition (Grant & Magee, 1998; Ruddle, Volkova, & Bulthoff, 2011; Ruddle, Volkova, Mohler, & Bulthoff, 2011; Waller, Loomis, & Haun, 2004) and others showing no benefit of such cues (Huffman & Ekstrom, 2019b; Li & Giudice, 2013; Mellet, Laou, Petit, Zago, Mazoyer, & Tzourio-Mazoyer, 2010; Waller, Loomis, & Steck, 2003). Even those studies reporting a benefit of body-based cues for survey knowledge acquisition have reported a relatively small benefit (Chance, Gaunet, Beall, & Loomis, 1998; Chrastil & Warren, 2013; He, McNamara, Bodenheimer, & Klippel, 2019; Waller & Greenauer, 2007; Waller et al., 2004), which stands in contrast to the large benefit of body-based cues in spatial updating tasks like triangle completion (e.g., Cherep et al., 2020; Kelly et al., 2020), and further calls into question whether spatial updating plays a central role in survey knowledge

acquisition. Therefore, it is not clear whether teleporting interfaces that vary in concordance within the concordance framework would align with results from past studies on the role of body-based cues on the acquisition of survey knowledge. Clarifying that gap is the goal of this research.

Overview of experiment

Teleporting interfaces are widely used in VR applications. Yet, the spatial cognitive costs associated with teleporting interfaces are not fully understood. The present study evaluates survey knowledge acquisition when using the partially concordant and discordant teleporting interface. It is not feasible to compare performance when teleporting with a full walking condition in which all self-motion cues are present because the VEs are rather large, but such a comparison will be important to explore in future work. The primary comparison in these studies is between partially concordant teleporting and discordant teleporting, which can be considered a manipulation of the availability of rotational self-motion cues (both visual and body-based). Recent research indicates that partially concordant teleporting leads to better spatial updating performance than does discordant teleporting (Cherep et al., 2020; Kelly et al., 2020). Whether the two interfaces differ in survey knowledge acquisition is unknown. However, past work (Cherep et al., 2020; Kelly et al., 2020) found that when rotational self-motion cues were available, spatial updating performance was reliably better than when no self-motion cues were available with discordant teleporting. Theories that propose a central role for spatial updating in survey knowledge acquisition (Klatzky et al., 1998; Montello & Pick, 1993; Richardson, Montello, & Hegarty, 1999; Wang, 2016) certainly predict such a difference in that rotational self-motion cues with partially concordant teleporting would lead to more accurate survey representations compared to discordant teleporting.

In this experiment, participants explored a large-scale VE learning the relative locations of objects using one of two teleporting interfaces: partially concordant teleporting or discordant teleporting. Participants' survey knowledge was assessed by completing an SOP pointing task in VR and a map drawing task. The importance of this research was to establish whether rotational self-motion cues when teleporting would impact the accuracy of acquired survey knowledge. Pre-registration and supplemental materials (demonstration videos) for Experiment 1 are available on the Open Science Framework (<https://osf.io/vpfja/>).

Hypotheses

H1: It was hypothesized that using a discordant teleporting interface will lead to larger pointing errors than when using the partially concordant teleporting interface.

H2: It was hypothesized that the discordant teleporting interface will lead to less accurate sketch maps compared to using the partially concordant teleporting interface.

Power Analysis

To determine the targeted sample size of 102 participants, a power analysis (G*Power) was conducted with the following parameters: means independent samples t-test between two groups, one-tailed test, Cohen's d effect size, $d = .50$ (medium effect size), alpha level = .05, minimum Power needed to detect an effect set at = .80. The estimated Cohen's d effect size, $d = .50$ were expected effects observed for a pointing task were based on a similar study that compared survey knowledge accuracy of participants between a VR head-mounted display with rotational self-motion cues and a desktop VR removing all body-based cues, and found a medium effect size Cohen's $d = .44$ (He, McNamara, Bodenheimer, & Klippel, 2019).

Method: Experiment 1

Participants

Undergraduate participants were recruited from undergraduate psychology courses at Iowa State University. Participants were compensated with course credit. Of 118 participants, 11 participants were removed in the final analysis due to the following reasons: two indicated they already had knowledge of the map from playing the videogame Counter-Strike, six were due to technical issues, one ended early reporting cybersickness, one had difficulty seeing without their eyeglasses, and one failed to follow the experimental instructions. A total of 107 participants, 60 women and 47 men were included in the final analysis, 51 were assigned to partially concordant teleporting (28 women, 23 men) and 56 were assigned to discordant teleporting (32 women, 24 men). Refer to Appendix for IRB approval.

Materials

The equipment consists of an HTC Vive head mounted display (HMD), which presents stereoscopic images at 1080×1200 resolution per eye, refreshed at 90 Hz. HMD field of view is 100° horizontal and 110° vertical binocular field of view. Graphics are rendered on a Windows 10 computer with an Intel Core i7-9700K processor and Nvidia GeForce RTX 2080 graphics card using Unity 3D software. Head position is tracked in three dimensions and orientation is tracked in three dimensions using the Lighthouse tracking system sold with the Vive. One wireless handheld controller, also sold with the Vive, was used by participants to control the teleporting interfaces and to respond on each trial during the SOP pointing task.

Teleporting Interfaces

When using the partially concordant teleporting interface, participants physically turned their body to rotate and teleported to translate in the VE. When using the discordant teleporting interface, participants teleported to translate and to turn in the VE. A virtual replica of the

handheld controller was always visible, and its position and orientation were linked to that of the actual controller. The partially concordant teleporting interface was controlled by positioning a white circle (30 cm diameter) with surrounding white ring (75 cm diameter) in the intended location on the ground plane (see Figure 3, left panel). A thin red line (virtual laser) extended from the joystick to the center of the white circle. The participant pressed and held the trackpad located on the top of the controller while manipulating the location of the teleport marker by pointing with the controller (similar to positioning a laser pointer). Releasing the trackpad teleported the participant to the selected location (orientation was unchanged). The discordant teleporting interface was controlled by positioning and orienting a magenta ring (height: 7.5 cm; outer diameter: 195 cm) with an arrow on one side (Figure 3, right panel). A thin red line extended from the joystick to the center of the ring. The participant pressed and held the trackpad button to bring up the teleporting ring, and rotated the ring by moving the thumb around the edge of the circular trackpad. Releasing the trackpad button teleported the participant to the selected location and orientation.

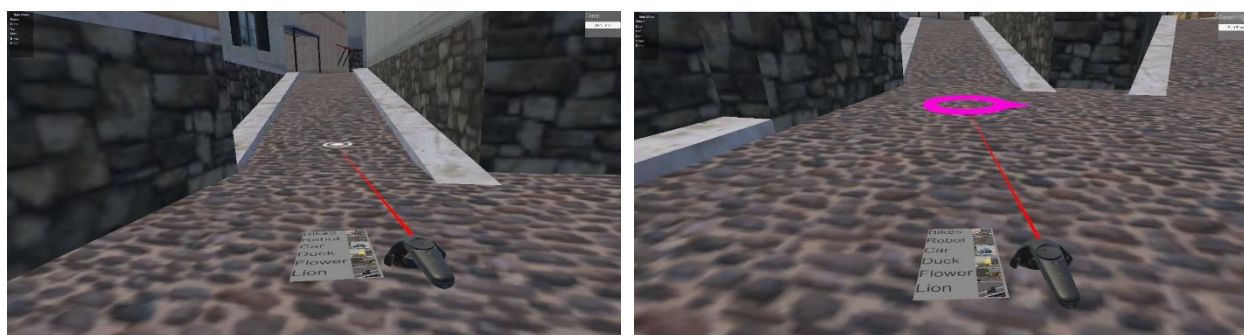


Figure 3. Screenshots taken from the participant's perspective while using the partially concordant teleporting interface (left panel) and the discordant teleporting interface (right panel).

Virtual environments

The "Italy" (Italian villa) map was imported from the first-person shooter videogame Counter-Strike (Valve Corporation) into Unity (Unity Technologies) and modified by introducing new objects and restricting access so that participants could not travel inside

buildings (see Figure 4). Exploration was confined to only paths outdoor. The Italy map was a multi-level VE with two floors accessible by stairs. The scale of this VE is considered to be “environmental scale” (Montello, 1993) because the entire VE cannot be viewed from one or a small number of locations and instead, requires participants to actively navigate and integrate spatial knowledge to learn about the relative locations of each object.



Figure 4. Birds-eye view of the Italian villa VE and the locations of six target objects. Participants were not exposed to this map during the experiment. The areas highlighted in green are located on the second floor of the VE.

Measures

Scene-dependent, orientation-dependent perceptual (SOP) pointing task (Figure 5) was used as a primary measure for survey knowledge. Participants were placed at one of the six landmark object locations and asked to point to all other remaining objects (e.g., “You are now standing at the Lion, please point the laser at the Duck.”). Participants completed 30 trials,

pointing to and from each pair of objects. The order was randomized and blocked by each landmark object and pointing to each landmark object was randomized. A bidimensional regression (BDR) analysis (Friedman & Kohlman, 2003) was used to analyze and compare map sketches drawn by participants to the target map to measure the fidelity of acquired survey knowledge. The sketch maps were scanned and resized to have an equal number of pixels in both width and height. The scanned maps were analyzed using the Gardony Map Drawing Analyzer: Software (Gardony, Taylor, & Brunyé, 2016).



Figure 5. Screenshots taken from the participant's perspective while performing the SOP pointing task. Instructions for each pointing trial was fixed on the Vive controller (left panel) and a virtual laser attached to the Vive controller was used to indicate the direction of their pointing response (right panel).

Procedure

Once the participant provided informed consent, the participant was fitted with the VR HTC Vive head-mounted display and used a Vive controller to teleport through the VE. Participants were provided training with one of the assigned teleporting interfaces. All participants stood in one fixed location in the middle of the laboratory surrounded by four small bumpers placed on the ground around their feet to prevent the participant from rotating out of place.

At the start of the experiment, the experimenter instructed the participant that they would have seven minutes (established as sufficient time from pilot data) to explore the VE and learn the locations of six objects in no particular order (bikes, rubber duck, car, flowers, lion statue,

robot) placed at various locations throughout the VE. They were specifically instructed to remember the relative direction of objects to each other because they would be tested after exploring and learning the location of all six objects in the VE and asked to complete a map drawing. An example of the pointing task trial was provided to the participant, “You are standing at Office and Labs, point to the Memorial Union. Instead, you will be performing the task using the objects you learn in this virtual environment.” All participants started at the same home location in the VE before fully exploring. The entire list of objects was accessible to the participant at any time by pulling up the Vive controller up to their field of view to view the list. Once a landmark object was discovered, the participant tagged the landmark object by pointing and pulling the trigger with the Vive controller activating a laser at the landmark object and feedback was provided on the list of objects indicating any remaining objects to search. If participants discovered all the objects with time remaining, they were instructed to continue exploring to learn the VE until the seven minutes had expired. An audible sound was triggered once the learning time expired. If the participant did not find all six objects, the participant was verbally guided by the experimenter to any unvisited landmark object(s). After learning, participants performed the SOP pointing task. After completing the SOP pointing task, participants were instructed to draw using pen and paper a birds-eye view sketch map of the VE they experienced including any paths, buildings, and all objects. A list of the objects was provided to ensure participants placed all the objects on the sketch map. The study took approximately 30 minutes to complete.

Results and Discussion: Experiment 1

Nineteen participants (partially concordant teleporting = 4, discordant teleporting = 15) were unable to find all the objects on their own within the time limit. Not finding all the objects

within the time limit happened more frequently in the discordant teleporting interface. However, this highlights an important difficulty associated with using the discordant teleporting interface. The conclusions are identical regardless of whether the analyses include those participants who did not find all objects in the allotted time. Therefore, the results include all participants.

Assumptions of normality and homogeneity of variance were tested for absolute angular errors and sketch maps. Absolute angular errors and sketch map scores were not normally distributed, as assessed by Shapiro-Wilk's test, $p < .05$. However, Welch's t-test is robust to deviation from normality (Delacre, Lakens, & Leys, 2017). Assumptions of homogeneity of variance were not violated, as assessed using Levene's Test, $p > .05$ with equal variances assumed between the two conditions (Moser & Stevens, 1992).

It was hypothesized that absolute angular error on the SOP pointing task would be larger after learning with the discordant teleporting interface compared to the partially concordant teleporting interface (Figure 7). Welch's independent samples t-test (Moser & Stevens, 1992) was conducted and a significant difference was found, pointing error was lower for the partially concordant teleporting ($M = 39.49$, $SD = 21.52$) compared to discordant teleporting ($M = 55.25$, $SD = 22.17$), $t(104.56) = 3.73$, $p < .001$, Cohen's $d = .72$, 95% CI [0.33, 1.11].

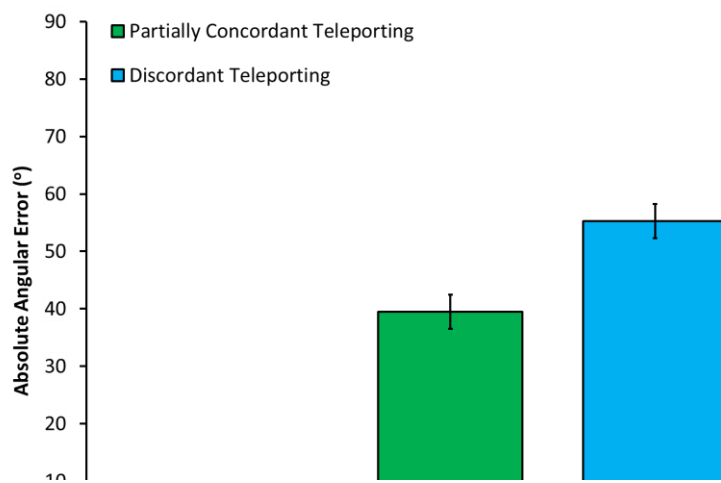


Figure 6. Average absolute angular error (in degrees) when performing the SOP pointing task in Experiment 1. Error bars represent ± 1 SEM.

Response time (in seconds) for the SOP pointing task were analyzed between the two teleporting interfaces using Welch's independent samples t-test $t(100.241) = 1.42, p = .159$, and there were no significant differences in response times, partially concordant teleporting ($M = 6.2, SD = 2.29$) and discordant teleporting ($M = 6.8, SD = 2.02$), Cohen's $d = .28$, 95% CI [.23, 1.42].

It was hypothesized that sketch maps would be less accurate when using the discordant teleporting interface. Map drawing accuracy (examples of sketch maps Figure 8) was analyzed by comparing average R^2 values calculated from bidimensional regression between the two teleporting interfaces (Figure 7). Welch's independent samples t-test was conducted and a significant difference was found, participants in the partially concordant teleporting produced maps that were more accurate ($M = .53, SD = .33$) compared to map drawings from participants using the discordant teleporting interface ($M = .36, SD = .30$), $t(101.02) = 3.95, p = .008$, Cohen's $d = .53$, 95% CI [0.14, 0.92].

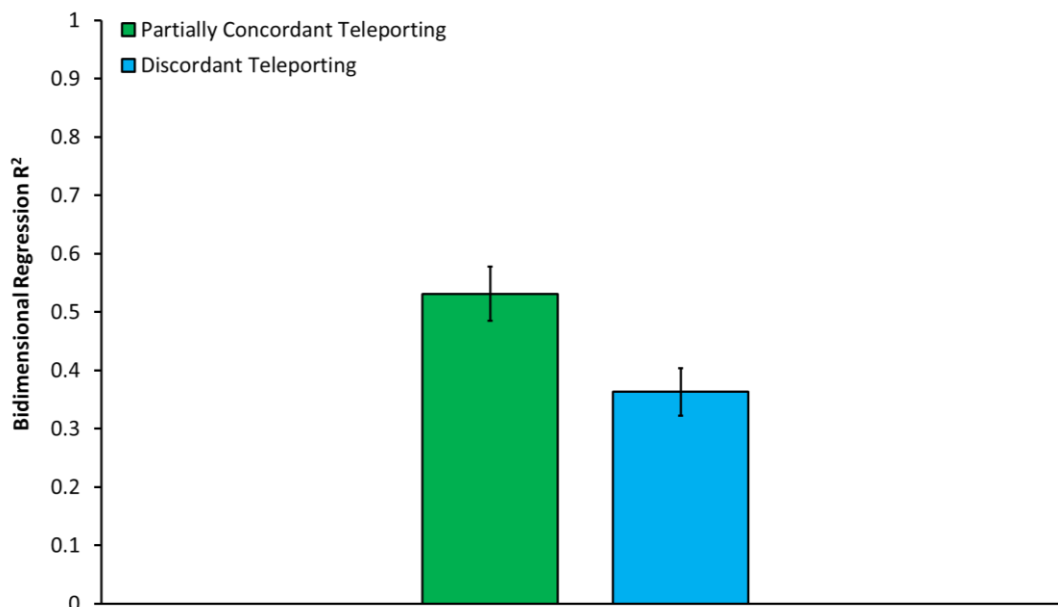


Figure 7. Bidimensional regression (R^2) for sketch maps in Experiment 1. Error bars represent ± 1 SEM.

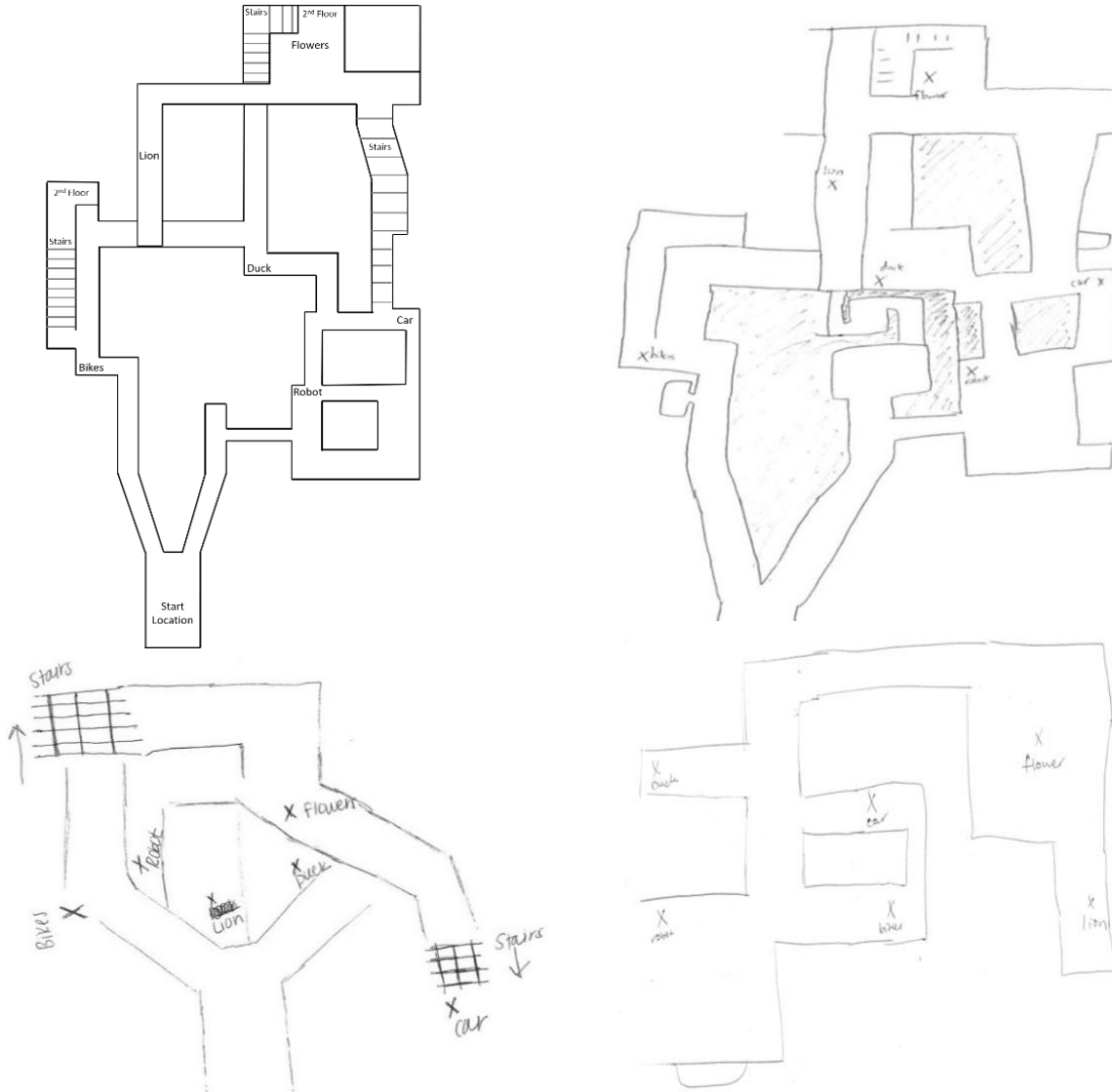


Figure 8. Examples of three sketch maps that differ in levels of sketch map accuracy: the target map (top left panel) is what all other sketch maps are compared to, a sketch map with greatest accuracy $R^2 = .94$ (top right panel), a sketch map with moderate accuracy $R^2 = .54$ (bottom left panel), and a sketch map with the lowest accuracy $R^2 = .04$ (bottom right panel). Each map drawn was from a different participant who explored the VE using the partially concordant teleporting interface. Note that the sketch map analysis only considered object locations and not other map features, such as corridors.

Previous research on the effect of teleporting interfaces on the acquisition of survey knowledge has not been well established in the research literature. Therefore, this experiment was set out to evaluate the effect of two types of commonly used teleporting interfaces on survey

knowledge when exploring a large-scale VE. Survey knowledge was assessed by employing a pointing task and sketch maps. Evidence from this study supports the hypothesis that partially concordant teleporting would result in more accurate survey knowledge, and this was confirmed for both sketch maps and pointing task measures. This experiment provides useful data with theoretical implications for supporting the theory that body-based cues (i.e., rotational self-motion cues alone) are not only meaningful for spatial updating (e.g., Cherep et al. 2020; Kelly et al., 2020; Klatzky et al. 1998), but that it also modulates the acquisition of survey knowledge when learning large-scale VEs. The results presented here are promising in that VR designers can adopt spatial cognitive principles to develop locomotion interfaces that reduce disorientation and aid in spatial learning.

Limitations and Future Work

Future work should consider evaluating whether access to all self-motion cues in a completely concordant locomotion interface in VR with translational self-motion cues (e.g., walking) would perform equally well or better than rotational self-motion cues alone when learning a large-scale VE. Based on prior research (Cherep et al., 2020; Kelly et al., 2020) on spatial updating, it would be expected that access to all self-motion cues during exploration should lead to more accurate survey knowledge. The lack of physical tracked space did not allow for making such a comparison in the current study. However, such a study is likely feasible in the future with hardware advancements using consumer VR headsets such as the Oculus Quest which allow users to explore large VEs untethered (e.g., in a gymnasium). More sophisticated omni-directional treadmills (e.g., KATWALK VR) allow researchers with limited laboratory space to conduct experiments with full-scale walking in large VEs, but whether such a device is considered concordant using the concordance framework is not yet clear.

Other gaps in spatial cognitive research underscore the need to evaluate whether environmental complexity (Carlson, Hölscher, Shipley, & Dalton, 2010) would exaggerate the negative effects of teleporting. For instance, many VEs often found in VR video games that require movement through large-scale VEs vary in complexity. In the context of teleporting in VR, this can be problematic because VEs vary in scale and their navigability, and the lack of body-based cues when teleporting exerts additional spatial cognitive costs that are likely to impact survey knowledge acquisition. Another way to vary environmental complexity can be accomplished by manipulating the total number of turns that are required to explore the VE. Turns are especially relevant to the distinction between partially concordant and discordant teleporting interfaces, which is fundamentally a manipulation of rotational self-motion cues.

CHAPTER 3. EXPERIMENTS 2 AND 3

Effect of testing on route learning using GPS navigation

Introduction

A tragic story of being lost during a hike in a forest took the life of a sixty-six-year-old nurse from Tennessee whose life-long goal was to walk the Appalachian trail that stretches more 2,100 miles from Spring Mountain in Georgia to Mount Katahdin in central Maine. In a recent book, Bond (2020) reports on the details of this unfortunate ordeal. Geraldine (Gerry) Largay was reported missing near Redington in July 2013 and it took over two years before they discovered her body in her tent surrounded by a rich dense forest. Gerry kept a detailed journal log of her hike and sent several text messages to her loved ones during this ordeal and with that, surveyors were able to somewhat piece together the string of events that led to her unfortunate demise. Based on Gerry's last location, surrounded by a rich dense forest with little to no landmarks around and no cellular signal, she became easily disoriented. It was later learned that Gerry was only half a mile off a backtrail, and if she continued in either direction, it would have led her straight out of the woods onto a trail. Many experts have speculated what went wrong and what Gerry could have done differently. However, family and friends who were very close to Gerry reported that she was not blindly foolish to attempt such a feat without any preparation. In fact, close ones described Gerry as being diligent in her preparation, doing practice hikes and so on. It was likely the "perfect storm" for Gerry to be disoriented. Feelings of being misplaced or disoriented in an unfamiliar environment can be dreadful for many, which likely explains also why some people shy away from forests because of the threat of being lost and not being able to find their way out again. It might also explain a recent phenomenon of our reliance on GPS devices that provide wayfinding support.

In the age of GPS, it is likely that we forget how easy it is to get lost. With smartphone devices at our fingertips, mobile based GPS devices (e.g., Google Maps) have become ubiquitous with obvious benefits of providing efficient real-time wayfinding support (with the exception of indoor environments). Researchers have been intrigued by this relationship between GPS devices and our navigational abilities. Laboratory studies have demonstrated that relying on GPS navigation can impair our wayfinding abilities (Fenech, Drews, & Bakdash, 2010; Gardony, Brunyé, Mahoney, & Taylor, 2013; Ishikawa, Fujiwara, Imai, & Okabe, 2008; Ruginski, Creem-Regeher, Stefanucci, & Cashdan, 2019). Our ancestors certainly did not have such a device handy and instead, they had to rely on their internal spatial knowledge to forage and travel long distances without getting lost because their very survival depended on it.

As we age, our capabilities for spatial knowledge acquisition and recall also decline. In the case of older adults who often experience problems with spatial navigation (Lester, Moffat, Wiener, Barnes, & Wolbers, 2017), GPS assistance is an extremely helpful tool. However, there might be one remedy to starve this age-related decline. Body exercises strengthen the muscles in our body. Analogous to our body, our brain is like a muscle and to strengthen those spatial abilities requires us to exercise those skills. For instance, neuroimaging scans among London taxi drivers show larger right posterior hippocampi compared to healthy controls (Spiers & Maguire, 2007). For London taxi drivers, this effect is largely a result of their years and years of extensive training studying the labyrinth-like streets of London (Wollett & Maguire, 2011). London taxi drivers exhibit extraordinary prowess when it comes to navigating between locations within London and they are not allowed to rely on a GPS device. London taxi drivers are said to go through a rigorous process that requires committing to memory 25,000 streets and 50,000 points of interest (e.g., pubs, clubs, galleries, monuments, and museums). Only then when

they can demonstrate navigating proficiently between those places are they allowed to work as a London (black cab) taxi driver (Beard, 2019).

Although most of the general population cannot be navigational experts, there might be ways to enhance spatial knowledge through principles in memory research. A robust phenomenon known as the testing effect (or “retrieval practice”) in which memory retrieval of learned materials benefits memory for later recall has repeatedly shown benefits in learning compared to restudying of the same materials. Generally, most of the research on the benefits of testing has largely been found with a variety of verbal materials such as word lists (Carpenter, 2009), reading passages (Roediger & Karpicke, 2006), and foreign language (Carrier & Pashler, 1992; Karpicke & Roediger, 2008). The benefits of testing have been shown both in laboratory settings and in applied settings (e.g., classrooms).

In a prototypical research design to study the testing effect, participants are first presented with a set of to-be learned materials (e.g., word lists, reading passages) to study for a certain amount of time. Afterwards, a subsequent phase occurs during which the studied information can either be re-presented for an additional study period (i.e., restudy condition) or subjected to a memory test (i.e., test condition; with or without corrective feedback) in which they are told to recall as much of the materials they can. Following this phase, typically a short-or-long retention interval (e.g., short distractor task – label all 50 states on this map) is introduced to induce some forgetting, and then the participant is given a final memory test on the information previously learned. Many variations of this paradigm have been closely examined by researchers, and studies continuously demonstrate the robust effect of testing which generally leads to better final test performance compared to restudying (see Kornell & Vaughn, 2016; Rowland, 2014).

Despite the strong evidence suggesting that testing leads to better learning, studies on the testing effect have mostly been limited to understanding the effects of testing on verbal materials. However, researchers have begun exploring the benefits of testing on nonverbal spatial materials such as information conveyed through maps, object arrays, and routes (e.g., Carpenter & Pashler, 2007; Carpenter & Kelly, 2012; Kelly, Carpenter, & Sjolund, 2015; Rohrer et al., 2010). Research on this topic is reviewed in more detail in the next section. To some extent, these studies have demonstrated similar benefits to memory for spatial learning, but Kelly et al. (2015) discovered some differences. To expand on prior research, the experiments presented here in Chapter 3 were aimed at exploring the boundary conditions of the testing effect on route knowledge acquisition. In some cases, the benefits for committing route knowledge to memory may outweigh the negative costs associated with relying on route guidance (e.g., Fenech, Drews, & Bakdash, 2010; Gardony, Brunyé, Mahoney, & Taylor, 2013; Ishikawa, Fujiwara, Imai, & Okabe, 2008; Ruginski, Creem-Regeher, Stefanucci, & Cashdan, 2019). For example, in such cases when there is equipment malfunction or limited GPS signal in indoor environments, the benefits of testing may prove to be an effective memory intervention for a variety of situations and may also improve spatial knowledge for those who suffer from poor spatial ability (e.g., “I need to use a GPS because my sense of direction is not very good.”). Other examples of relying on GPS navigation assistance have led to catastrophic incidents because drivers were disengaged with their surroundings (Lin, Kuehl, Schöning, & Hecht, 2017).

Despite numerous studies describing the negative effects of GPS use on the acquisition of spatial knowledge, there is very little research that has examined whether the suppression of memory retrieval (i.e., testing) is a contributing factor. Therefore, the two experiments described here examine whether testing with feedback benefits memory for route knowledge compared to

studying (i.e., following GPS-like turn-by-turn directions during route learning) in a driving simulator task in a virtual city. The importance of this work is not only to understand how GPS use impacts route learning compared to recalling routes from memory, but to also explore memory interventions that would benefit memory for route knowledge.

Relationship between GPS use and spatial knowledge acquisition

It is clear that GPS devices are a useful tool for navigating to locations in unfamiliar environments. On the other hand, GPS devices are not always perfect, and in some cases, the user might misread the guidance system leading the user off course. With current GPS route guidance (e.g., Google Maps), there is not likely any concern for navigating off course. In fact, many have reported a sense of relief when using their GPS devices (Kim & Dey, 2009). However, relinquishing the decision-making during navigation could lead to poorer spatial knowledge. In this section, I will review evidence from studies suggesting that reliance on GPS devices negatively affects spatial knowledge acquisition.

Although little is known about the relationship between lifetime GPS use and spatial navigation ability among individuals, there are several laboratory studies that suggest relying on GPS route guidance does negatively impact accurate spatial knowledge acquisition (Fenech, Drews, & Bakdash, 2010; Gardony, Brunyé, Mahoney, & Taylor, 2013; Ishikawa, Fujiwara, Imai, & Okabe, 2008). In one study on the effects of GPS route guidance on spatial learning (Ishikawa et. al 2008), participants learned six different routes on foot: one group used a GPS device to navigate and one group walked the routes guided by the experimenter first, and then walked the route again on their own without any aid. After participants reached the target location for each route, participants were asked to point back to the starting location and draw the route. Results revealed that the GPS group had poorer direction estimates and route drawings

than the direct-experience group that was led by the experimenter for each route. In addition, other measures revealed that on the final test, the GPS group made significantly more stops, traveled longer distances, and exhibited slower travel speed.

One explanation for why GPS negatively affects spatial learning is that GPS route guidance reduces processing of environmental information, perhaps because attention is directed towards the GPS rather than the environment. In the study by Ishikawa et al. (2008), it is likely that GPS users were focusing on the continuously updating screen of the device which impaired their ability to focus on their environment, thus causing participants to pay less attention to their surroundings. This was evidenced in a study (Hejtmánek, et al., 2018) with the use of eye-tracking. Participants explored a virtual town on desktop VR navigating to-and-from 21 different locations with access to a bird's-eye view GPS map. Participants were asked to navigate to each target location and once they arrived at the target location, the GPS map was hidden and they were asked to point back to the start location. After the pointing response, they were asked to navigate the shortest route back to the preceding start location. This was repeated for all 21 locations. Participants were also asked to fill in a blank map by providing either the location name, location position, or both. GPS map use was completely voluntary and time spent viewing the route guidance map was measured through eye-tracking. More time spent viewing the GPS map was associated with larger pointing errors, longer path lengths, and more incorrect placement of learned locations and location naming. This further suggests that the use of a route guidance system reliably reduces visual processing of the environment.

It is argued that navigators are occasionally glancing at their smartphones or GPS device even if it is placed peripherally in the driver's field of view (FOV) (Bergasa, Almeria, Almazán, Yebes, & Arroyo, 2014). Therefore, if using a GPS device causes a lack in visual processing

through visual disengagement, then one might think to use a different modality such as acoustic turn-by-turn directions. One study examined whether acoustic turn-by-turn directions would reduce the divided attention in visual processing (Fenech, Drews, & Bakdash, 2010). Participants performed a wayfinding task in a virtual town using in a driving simulator task on desktop VR with 180-degree field-of-view. All participants were shown a map of the optimal route they were required to learn. The GPS group received acoustic turn-by-turn navigation through the virtual town (e.g., “In 0.5 miles turn left”) while the control group received no wayfinding support. On final test, both groups had to reproduce the learned route without guidance. It was found that the GPS group took significantly longer than the control group to reproduce the route. Furthermore, the control group demonstrated better memory for visual scenes experienced along the route. The authors speculate that the deficit in route learning in the GPS group is related to inattentive blindness (i.e., a failure to notice visible changes in the environment) caused by dual-tasking interference.

Evidence from a recent study (Ruginski, Creem-Regeher, Stefanucci, & Cashdan, 2019) suggests that GPS use is significantly associated with poor performance on various spatial tasks: mental rotation scores, perspective taking, distance estimates and pointing estimates. Participants navigated several different routes that were interconnected on a virtual campus using desktop VR and were tasked with learning the locations of different landmarks throughout. Although this study did not manipulate GPS use, participants were asked about their habits with using GPS. It was revealed that lifetime GPS use was indirectly and negatively associated with environmental learning through spatial transformation abilities (i.e., mental rotation and perspective taking). However, the directionality is unclear, whether long-term GPS use negatively affects environmental learning by decreasing spatial transformation abilities or whether low spatial

transformation abilities leads to increase GPS use. Navigating without a GPS device might hone spatial skills and benefit from desirable difficulties.

In a cross-sectional and longitudinal study, Dahmani and Bohbot (2020) examined lifetime GPS experience of 50 healthy adults who drive a minimum of four days a week. Based on the behavioral measures, results from both the cross-sectional and longitudinal study revealed that greater lifetime GPS use was associated with lower performance on various facets of spatial memory, including spatial memory strategy use, cognitive mapping, and landmark encoding using virtual navigation tasks. These findings also suggest that people who have greater GPS reliance may rely less on their hippocampus for navigation which is consistent with previous results (Javadi et al., 2017).

Conversely, London taxi drivers are a unique group and one example of honing spatial skills that require extensive and rigorous training to become a certified taxi driver in London. It has been found that London taxi drivers possess very complex cognitive maps because of their extensive training and experience (Beard, 2019). Using neuroimaging (Maguire et al., 2000), London taxi drivers compared to healthy controls showed significantly greater gray matter volume in the right hippocampus (associated with cognitive map formation) compared to the left hippocampal area. This difference could be attributed to the right posterior supporting the role of cognitive maps as it was found to be positively correlated with time spent as a taxi driver. While the results are correlational, this highlights some promise that structural changes in the brain could be caused by long-term use of spatial knowledge.

Navigators who use GPS-like route guidance may pay more attention to the device than their surroundings (Hejtmánek et al., 2018; Ishikawa et. al 2008) which leads to a difficulty in learning due to divided attention (Gardony et al., 2013). The fact that participants learn less

accurate spatial information about GPS-guided routes supports the theory that using GPS lessens the need to pay attention to our surroundings and update our position. Evidence from these studies adds to the growing picture that using a GPS device is a likely source for poorer spatial knowledge acquisition.

Effect of testing on spatial learning

It is likely that you have experienced traveling an unfamiliar route while guided by GPS. Perhaps you used it once or twice on the same unfamiliar route. After some time, you likely relied less and less on the GPS device and became increasingly more comfortable relying only on your memory for route knowledge. Alternatively, you could have relied on your GPS device while traversing the unfamiliar route the first time, and then attempted to retrieve that route from memory the next time. Retrieving the route from memory could lead you off course if your memory fails. However, research on the benefits of testing indicate that retrieval could improve long-term retention of the route. However, relatively little is known about the benefits of testing on route knowledge.

Many studies have found that recalling information significantly improves retention of that information when compared to restudying the same information. This is referred to as the testing effect (Roediger & Karpicke, 2006). This effect has been studied using stimuli that require verbal responses such as word lists (Carpenter & Delosh, 2006), foreign language vocabulary (Pyc & Rawson, 2010), prose passages (Butler, 2010), paired associates (Carpenter, 2009), trivia questions (Kornell, Hays, & Bjork, 2009), and foreign language vocabulary (Carrier & Pashler, 1992). Although research studies have reliably demonstrated the positive effects of testing on memory recall, the mechanisms that underlie why testing benefits learning are unclear.

There is a lack of research on the benefits of testing in spatial cognitive domains and what is perhaps one of the most important aspects of spatial learning is successful navigation using route knowledge. More recently, other studies have begun to explore the effects of testing in other domains outside of verbal materials and has shown to improve memory in spatial domains such as: visuospatial map learning (Carpenter & Pashler, 2007), spatial arrays of objects (Carpenter & Kelly, 2012), and route knowledge when movement errors were prevented (Kelly, Carpenter, & Sjolund, 2015). However, the very few research studies that do exist have not explored more complex forms of spatial learning (e.g., route and survey knowledge) and have very little ecological validity.

In a study on the effects of testing on map learning (Carpenter & Pashler, 2007), participants studied two two-dimensional maps with 12 distinct features on each map (e.g., trees, golf course, bathroom, etc.). One map was studied for 120 seconds. The other map cycled through repeated presentations in which one map feature was missing, and the participant attempted to recall the missing feature. Total presentation time was equated across conditions. Map learning was followed by an unrelated distractor task for 30 minutes. At final test, participants were given blank sheets of paper and instructed to draw both maps with all the features they could recall. Map drawing accuracy measures demonstrated an overall benefit to testing compared to restudying.

Consider a real-world example: if you learn the building locations of Beardshear Hall and Curtiss Hall by always using the vantage point from Agronomy Hall, does this help you later when you must navigate from Curtiss Hall to find your way to Beardshear Hall? In other words, does learning from one perspective convey benefits when retrieval occurs from other perspectives? One study (Carpenter & Kelly, 2012) examined whether the benefit of testing

when learning a spatial array of objects from one vantage point transfers to other novel vantage points. All participants viewed and studied an array of objects in a small-scale VE from a single vantage point in the first-person (i.e., egocentric) view. Participants wore a VR HMD and studied eight different objects for 90 seconds from a single vantage point from the 0° degree perspective, after which the objects disappeared. The participants then moved to another room and were asked to perform a series of judgments of relative direction (JRDs) on a desktop computer. For example, “Imagine standing at the ball, facing the soap. Point to the plant.” Six unique JRDs for each of the eight imagined perspectives, spaced every 45° degrees from 0° to 315° resulting in a total of 48 JRD trials. During initial learning, participants completed three repetitions of the 6 JRDs from the 0° degree perspective. At final test, participants completed all 48 JRD trials from eight imagined perspectives. Participants responded by rotating a radial line on the screen until it pointed in the appropriate direction. In the study condition, the correct pointing direction was always shown on the screen and participants simply had to match the correct direction. In the other two conditions, test only and test plus feedback, participants completed the same JRDs by retrieving the object locations from memory, with and without feedback. After completing a series of distractor tasks for 10-minutes, the participants completed a final test of JRDs. Results revealed a significant memory advantage for both the test and test plus feedback groups compared to the study-only condition. This was also true for both the learned perspective and novel perspectives that were not from the 0° degree perspective. Performance between the two test conditions were not significantly different. Evidence from this study demonstrates not only a benefit of testing for materials learned from one perspective, but also that testing benefits transfer of spatial learning.

A similar investigation was conducted to examine whether testing would benefit near-and-far transfer of spatial learning (Brunye, Smith, Hendel, Gardony, Martis, & Taylor, 2020). Across four experiments, participants studied a map of a large-scale VE with 21 labeled landmarks and participants were assigned to engage in either study or test (i.e., retrieval practice). Near and far transfer was defined by the spatial transformations required on the final test. For example, studying a map and then replacing learned items on the same map (e.g., Carpenter & Pashler) involves no spatial transformation. On the other hand, studying a map and then pointing to learned locations while standing in the learned environment may require multiple spatial transformations (e.g., from a map view to a first-person view, and from a fixed learning perspective to a flexible test perspective). In both the study and test group, participants were provided four learning opportunities to learn a map, followed by a final test. The test group was given an opportunity to study the map like the study group, except that afterwards the test group engaged in a map reconstruction task by arranging the different landmarks on a blank road map, and this set was repeated twice before the final test. In one experiment, at final test participants in both study and test groups were instructed to reconstruct the learned map by arranging the 21 different landmarks on a blank road map from memory and the test group outperformed the study group (similar to the results reported by Carpenter & Pashler, 2007). In another experiment, using the same methods described above, participants at final test were instructed to perform a series of JRDs (“Imagine standing at the Market, facing the Bakery. Point to the Gym.”) from perspectives that were aligned or misaligned with respect to the orientation of the map during learning. Results here also demonstrated a benefit of testing for both aligned and misaligned perspectives compared to the study group suggesting a near-to-medium transfer of spatial learning (similar to the results reported by Carpenter & Kelly, 2012). To test for

medium-to-far transfer, in one experiment, participants at final test were instructed to perform JRDs not from a birds-eye perspective, but from a first-person perspective in the VE itself. Therefore, participants had to transform the studied map to a perspective that was not learned and perform JRDs. Results revealed there was no difference in performance between the test and study group. A follow-up experiment was conducted in which participants at final test were instructed to navigate between the different landmarks and again, no difference was found between the test and study group. To summarize, there is clear evidence that testing does benefit spatial learning when the demands of the task require small to medium spatial transformations between the learned and tested materials, but large spatial transformations between learned and tested materials may eliminate the benefits of testing.

GPS use makes it possible to repeatedly follow the same route without memory retrieval (i.e., without testing). One study (Kelly, Carpenter, & Sjolund, 2015) examined whether testing would enhance memory for route learning. Participants learned which correct sequence of doors to select to get through 30 virtual rooms on desktop VR. Each virtual room contained three doors and a unique object (e.g., large plant, bowling pins, etc.) in the middle of the room which served as a landmark cue, as one would use when connecting a sequence of paths between landmarks. In the study condition, participants learned the correct sequence by navigating through the correct sequence of doors (highlighted in green). In the test condition, participants learned by approaching a door before receiving feedback. At final test, participants navigated through the same series of rooms without any feedback. Unexpectedly, the results in two of the experiments demonstrated a reverse testing effect, in which the study condition reliably outperformed participants in the test condition. Three follow-up experiments were conducted using the same paradigm except participants received feedback about their decision prior to traveling to the

selected door, thereby preventing participants from moving toward incorrect doors. When this occurred, a benefit of testing was observed. Results revealed that the number of incorrect doors was significantly lower in the test condition compared to the study condition, with the caveat that error movements were prevented. The authors speculated that the reverse testing effect that occurred when movement errors were allowed may be in part due to the procedural nature of route learning (Golledge, 1991).

Effective navigation is an important goal of spatial learning, and in many real-world contexts such as navigation training for firefighters or search and rescue teams, individuals must reach a destination from a starting location committing the fewest navigational errors possible. When relying on a GPS device for route guidance, a navigator is not likely to make any errors when traversing an unfamiliar route. Conversely, the navigator also has the option to retrieve route knowledge, which carries the possibility of producing errors such as wrong turns and backtracking or getting lost. This act of recalling a route from memory could be more beneficial for long-term retention. However, research on the testing effect indicates that route knowledge may not benefit from memory retrieval (Brunyé et al., 2019; Kelly, Carpenter, & Sjolund, 2015).

Overview of experiments

These experiments address whether route learning is impaired by repeatedly following GPS guidance, as compared to a memory retrieval condition. Although there has been little research on the effect of testing on nonverbal materials, the majority of the research highlighted in this chapter suggests that testing does improve spatial learning. However, most of that research has involved survey knowledge (i.e., knowledge of object-to-object relationships), and the scant research investigating route knowledge indicates that the testing effect does not always occur (e.g., Brunyé et al., 2019; Carpenter & Pashler, 2007, Carpenter & Kelly, 2012, Kelly,

Carpenter, & Sjolund, 2015). Furthermore, the existing research on route learning used stimuli that differ considerably from the typical real-world context in which route guidance is used. The experiments described here represent an increase in ecological validity over past work, while maintaining the experimental control needed to evaluate the effect of testing on route learning.

The work presented here is aimed at exploring whether testing improves route learning in a virtual city using a driving simulator compared to a restudy condition with GPS-like turn-by-turn directions. It is likely that traveling the same repeated route eventually requires no navigational assistance. However, several different studies reviewed here suggest that GPS use is associated with poorer spatial knowledge.

Experiments 2 and 3 compared the effect of testing versus study on pre-defined route using a driving simulator task in a large virtual city. In Experiment 2, participants in the study condition were provided four learning opportunities by repeatedly following route guidance and in the test condition, participants completed two trials with route guidance followed by two test trials. For the final test, participants in both study and test conditions returned to the lab after 2-days and navigated the same predefined route from memory. In Experiment 3, the number of trials was modified, participants in the study condition completed three study trials and in the test condition, participants completed one study trial followed by two test trials, and then the final test. Other than reducing the number of learning opportunities, Experiment 3 was nearly identical to Experiment 2. It was hypothesized in Experiments 2 and 3 that participants in the test condition would commit significantly fewer errors than the study condition.

Method: Experiment 2

Participants

Sixty-seven undergraduate students (35 Females and 32 Males) at Iowa State University participated in exchange for course credit. Six participants did not return for the second session

of the experiment. Of the 61 participants, 31 were assigned to the study condition (17 Females, 14 Males) and 30 were assigned to the test condition (15 Females, 15 Males). Gender was approximately balanced across the two conditions. No other demographic information was collected. Refer to Appendix for IRB approval.

Hardware and software

The virtual environment was displayed on a 22" inch desktop monitor, which was presented at $1,280 \times 1,024$ resolution at 60 frames per second. Vizard software (WorldViz, Santa Barbara, CA) was used to render graphics on a desktop computer with Intel Core2 Quad processors and Nvidia GeForce GTX 285 graphics card. The Logitech G920 Driving Force Steering Wheel was used for the driving simulator (Figure 10).



Figure 9. Logitech driving simulator setup with pedals (left panel). Participants were only required to use the steering wheel and the gas pedal to drive through the virtual city.

Stimuli

The large-scale virtual city was created using City Engine (www.esri.com/software/cityengine) and the total area of the city covered approximately 35 km².

The virtual city habited hundreds of unmarked city buildings, downtown shops, downtown city

center, and suburban areas (Figure 10). The virtual city was intentionally designed to not include any visible street names in order to reduce the likelihood of participants using a verbal learning strategy.

A bird's-eye map of the virtual city (Figure 11) highlights the predefined route that participants were required to learn, which included nine predefined turns at various intersections. Across all predefined intersections, there was a range of 2 – 4 possible turns (see Table 1). Maximum linear speed of movement was approximately 5.4 meters per second. At maximum speed, the route takes 166 seconds to complete without stops.



Figure 11. Screenshot from the participant's perspective of the virtual city on the pre-defined route.



Figure 10. Birds-eye map of the virtual city. Arrows (in yellow) trace the predefined route that participants were instructed to follow during learning. Participants were not exposed to this map during any part of the experiment.

Table 1. The number of turns in sequence from start to finish and number of turn decisions at each predefined turn decision. For example, at Turn 1 (Start) for a 3-way turn means that participant had three choices to either go left, right, or continue straight (coming onto a 4-way intersection). Also, this table does not include the many intersections for which the correct response was to go straight.

	Turn 1 (Start)	Turn 2	Turn 3	Turn 4	Turn 5	Turn 6	Turn 7	Turn 8	Turn 9 (Finish)
No. of possible turns	3-way turn	3-way turn	2-way turn	4-way turn	3-way turn	3-way turn	3-way turn	2-way turn	3-way turn

Design

In a between-participant design, participants were randomly assigned to either the study condition or test condition. Participants were provided four learning opportunities and were required to return approximately 48 hours (i.e., if the participant began on Monday at 8am, they were scheduled to return at approximately the same time on Wednesday) later to the lab and complete the final test (see Figure 12 for procedural diagram). GPS-like route guidance was provided by displaying green directional arrows on the road path as turn-by-turn directions (left panel in Figure 13). The green arrows were placed at each of the decision points and participants were instructed to follow that path until the next directional arrow was presented. Although this does not resemble the ways in which people actually receive turn-by-turn directions in real-world contexts, the intention was to avoid the confound of dividing the participant's attention because that was not central to this study.

Participants in the study condition were provided turn-by-turn directions in the form of green directional arrows on the road. This was repeated for all four learning trials. In the test condition, participants were guided with turn-by-turn directions during the first two learning trials. After two study trials, initial testing began and participants navigated the predefined route from memory (right panel in Figure 13) with corrective feedback for any incorrect turn

produced. Corrective feedback was required because if one incorrect turn was produced, the participant would continue off course. For example, if a participant produced an error by turning in the wrong direction from the predefined route, the participant was discretely teleported back to the preceding location after the incorrect turn was produced, and a directional arrow appeared as corrective feedback for 1.5 seconds, allowing the participant to observe the feedback and correct their turn. If the participant was driving on a straight path that was not near any of the predefined intersections and produced an error (e.g., erroneously turning left onto a street instead of continuing straight), the participant was brought back to the preceding location before the error was made but no directional arrow was provided. Participants were verbally instructed about the different types of corrective feedback prior during training. After participants completed all four learning trials, the experiment session ended, and they were scheduled to return approximately 48 hours later for the final test.

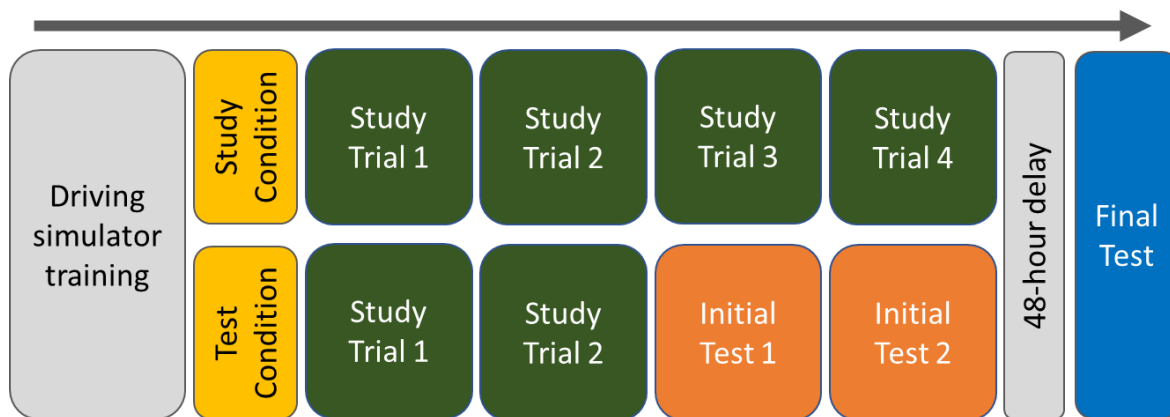


Figure 12. Flowchart of procedures for Experiment 2.



Figure 13. Example of the participant's perspective during learning. The same intersection is shown with (left panel) and without (right panel) turn-by-turn route guidance. A demonstration video of the two conditions can be viewed here: [Demonstration of study and test conditions](#)

Errors were measured by recording each incorrect turn produced along the predefined route during initial tests (test condition only) and at final test (for study and test conditions). Furthermore, there were two ways that errors in the test condition were coded: 1) errors produced during initial tests were measured to evaluate to whether errors were repeated on subsequent initial tests (i.e., initial test 1 to initial test 2), and at final test (i.e., initial test 2 to final test), and 2) whether any errors produced at final test occurred on either initial test 1 or initial test 2. For example (Figure 14), during initial test 1 or 2, if a participant incorrectly continued straight at a specific decision point instead of correctly turning left, and the exact same error was produced on subsequent tests, this was considered a *repeated location, same turn direction* error (Figure 14, top row). Using a similar example, if a participant on an initial test incorrectly turned right at a specific decision point instead of correctly turning left, but on subsequent tests continued straight, this was considered a *repeated location, different turn direction* error (Figure 14, second row). If an error was produced during initial testing, but that same error was not repeated (i.e., corrected) on subsequent tests, then that was coded as a *did not repeat* error (Figure 14, third row). Lastly, any errors produced at final test but did not occur at either initial test 1 or initial test

2, this was considered as *new errors* (Figure 14, last row). The different types of errors were measured purely for exploratory analyses as no predictions were made with repeated errors.

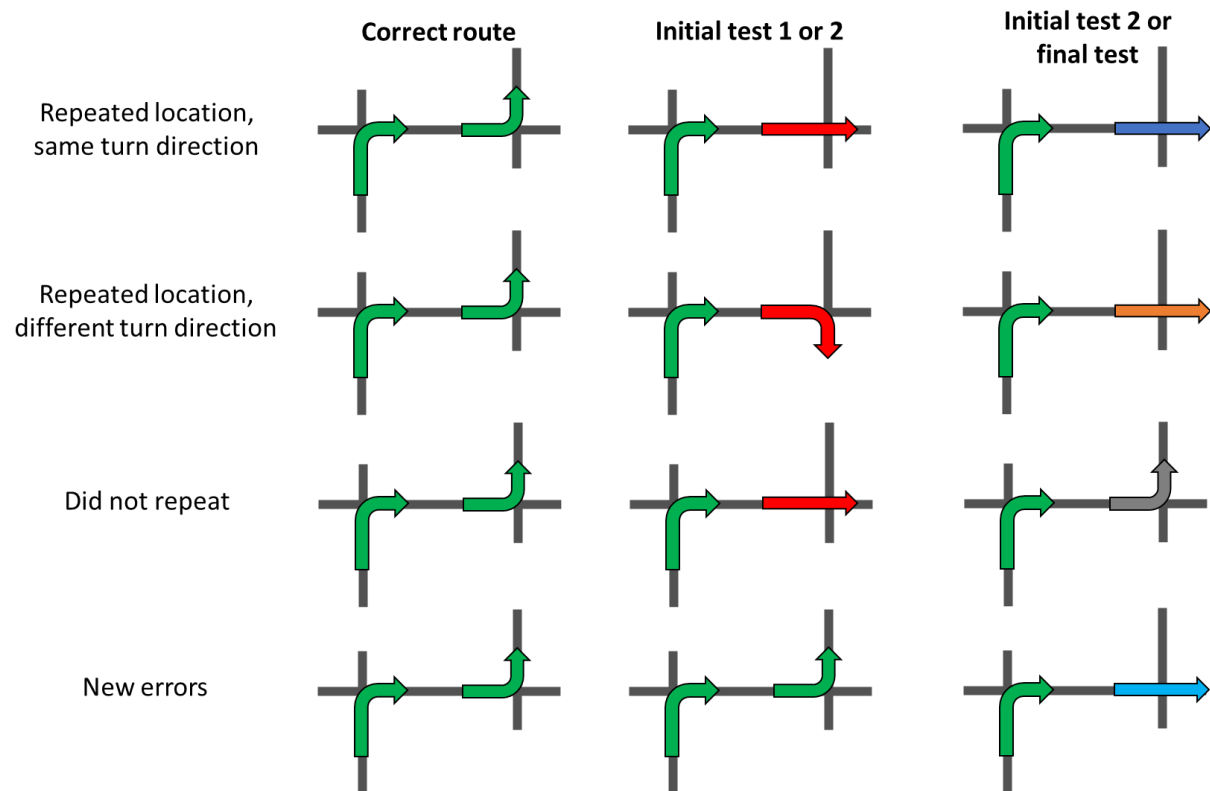


Figure 14. Examples of different types of errors (test condition only) that were produced during initial tests and repeated on subsequent initial tests (or at final test), and errors produced at final test that did not occur on previous initial tests. Green arrows indicate the correct turn response. Red arrows indicate an error produced on an initial test. Blue, orange, grey, and light blue arrows represent errors produced on subsequent tests (or at final test).

Procedure

Once participants provided informed consent, they were seated at the driving simulator and provided training with the driving simulator during which they performed several left and right turns in a different neighborhood of the same city used in the experiment. Once participants felt comfortable with the driving simulator, they were instructed navigate a predefined route in a different part of the virtual city, and that they would return to the laboratory approximately 48-hours later and navigate the same predefined route from memory. Participants were also

instructed to ignore driving rules (e.g., stopping at a stop sign), and to always stay on the road. When participants arrived at the destination, an audible bell was played to indicate the end of the trial and a bell horn was played when all trials were completed. Participants in the study condition were told to learn and navigate the predefined route by repeatedly following the directional arrows provided throughout the route. Participants in the test condition were provided the same instructions as the study group, but were instructed that after two study trials, they would navigate the same predefined route from memory. When participants completed the learning trials, they were dismissed and scheduled to return to the laboratory 48-hours later for the final test. At final test, all participants regardless of the learning condition were verbally instructed that their goal was to navigate the same predefined route from memory and that feedback would occur in the event an incorrect turn was made. The decision to provide feedback when an error was committed was because participants would likely continue navigating the incorrect path if not returned to the predefined route. The first phase of the study took 30 minutes or less to complete. The final test phase took less than 10 minutes to complete.

Results and Discussion: Experiment 2

Assumptions of normality and homogeneity of variance were tested for final test errors between study and test conditions. Final test errors were not normally distributed for both study and test conditions, as assessed by Shapiro-Wilk's test, $p < .05$. However, Welch's t-test is robust to deviation from normality (Delacre, Lakens, & Leys, 2017). Assumptions of homogeneity of variance were not violated, as assessed using Levene's Test, $p > .05$ with equal variances assumed between the two conditions (Moser & Stevens, 1992).

It was hypothesized that testing would benefit route learning, producing significantly fewer final test errors in the test condition compared to the study condition. An independent samples t-test was conducted and revealed no significant differences in the number of final test

errors between the test ($M = 2.47, SE = .39$) and study conditions ($M = 2.55, SE = .43$), $t(59) = 0.14, p = 0.89$, Cohen's $d = 0.04$, 95% CI [-1.08, 1.24]. In addition to the standard null hypothesis significance testing reported here, a Bayesian analysis was conducted to provide strength in evidence in favor of the null. Results indicate 3.81:1 odds in favor of the null (JZS prior, scale r on effect size = .71 for a medium effect; Rouder, Speckman, Sun, Morey, & Iverson, 2009), which is considered “substantial” evidence in favor of the null. This provides support that the group means likely come from the same distribution. Such analyses can be used to provide evidence in support of the null hypothesis (for a review, see Gallistel, 2009).

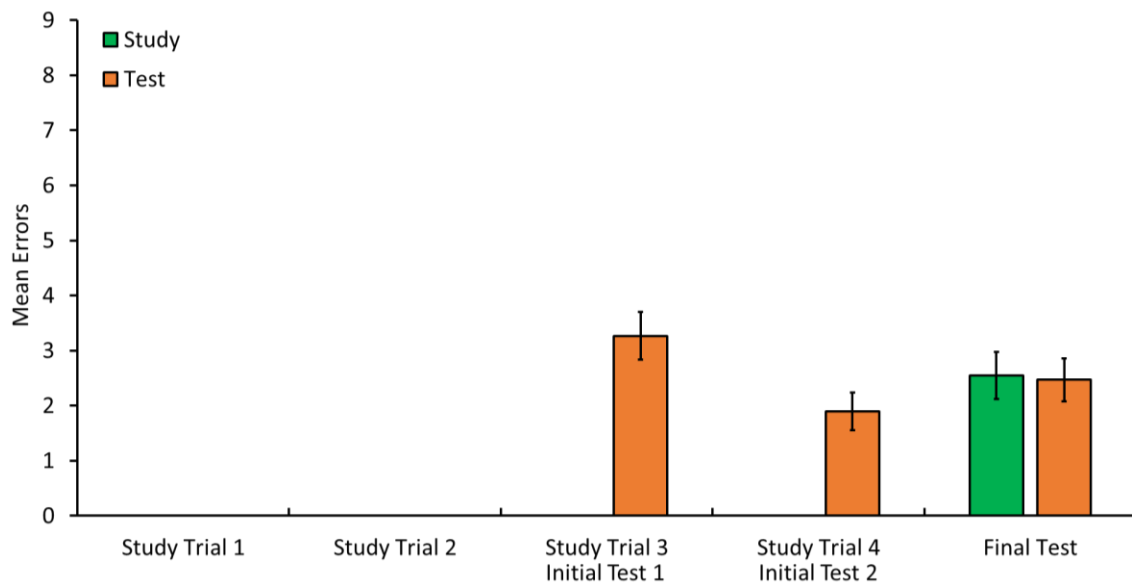


Figure 15. Mean total errors in Experiment 2 for participants in the Study and Test conditions across learning trials and at final test. Mean errors were always zero on study trials during learning. Error bars represent +/- 1 SEM.

Results from Experiment 2 indicate that testing did not produce a memory advantage in route learning over studying as hypothesized. It is possible that the testing effect was not found because of the procedural nature of the route learning task. It is also possible that the testing effect was not found because final test performance was too close to ceiling. If errors were produced at each decision point along the predefined route, that would total nine errors (note that

more errors could occur if participants incorrectly turn instead of going straight, although these errors rarely occurred). In that context, the average number of errors in this sample seems low. Therefore, one learning opportunity was removed in Experiment 3 designed to make the task more difficult, in the chance that the testing effect in Experiment 2 was not observed due to near-ceiling performance. Creating difficulty during learning has been shown to impair initial test performance but enhance final test performance (see Bjork, 1994; Bjork & Bjork, 2011). Therefore, it is expected that fewer learning opportunities should increase the difficulty. Other options include manipulating the predefined route by increasing the path length or increasing the number of decision points. The advantage of changing the number of learning opportunities is that it allows for comparisons between experiments if a testing effect is observed in the Experiment 2. To summarize, aside from the number of learning trials, Experiment 2 was identical to Experiment 3.

Method: Experiment 3

Participants

Sixty participants (31 Females, 29 Males) were recruited through the undergraduate psychology pool at Iowa State University and participated in exchange for course credit. Nine participants did not return for the second session of the experiment. Of the 51 participants, 26 were assigned to the study condition (11 Females, 15 Males) and 25 were assigned to the test condition (12 Females, 13 Males).

Stimuli, Design, and Procedure

Stimuli were identical to those in Experiment 2. The design was modified by removing one learning trial, resulting in a total of three learning opportunities (see Figure 16). The study condition had three study trials with turn-by-turn directions and the test condition was provided

one study trial with turn-by-turn directions and the remaining two initial test trials involved testing with feedback.

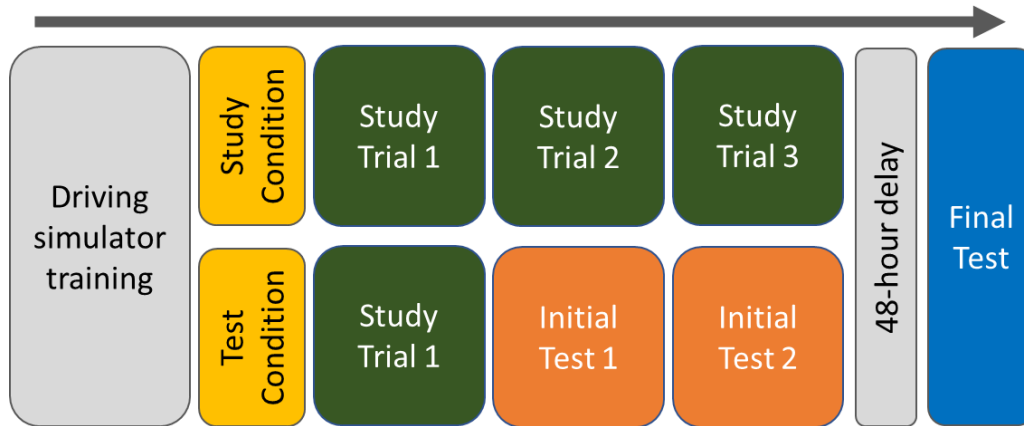


Figure 16. Flowchart of the procedures for Experiment 3.

Results and Discussion: Experiment 3

Assumptions of normality and homogeneity of variance were tested for final test errors between study and test conditions. Final test errors were not normally distributed for the study condition $p < .05$, but final test errors for the test condition were normally distributed $p > .05$ as assessed by Shapiro-Wilk's test. However, Welch's t-test is robust to deviation from normality (Delacre, Lakens, & Leys, 2017). Assumptions of homogeneity of variance were not violated, as assessed using Levene's Test, $p > .05$ with equal variances assumed between the two conditions (Moser & Stevens, 1992).

It was hypothesized that testing would benefit route learning resulting in significantly fewer final test errors than the study condition. An independent samples t-test was conducted and revealed no significant differences in the number of final test errors between the test ($M = 4.08$, $SEM = .53$) and study conditions ($M = 4.08$, $SEM = .47$), $t(49) = 0.004$, $p = .99$, Cohen's $d = 0.00$, 95% CI [-1.43, 1.42]. Like Experiment 2, no effect of testing was observed. However, despite the increased difficulty reflected in overall errors in Experiment 3 to reduce near-ceiling

effects found in Experiment 2, no effect of testing was observed. Bayesian analyses indicate 3.56:1 odds in favor of the null (JZS prior, scale r on effect size = .71 for a medium effect), which is considered “substantial” evidence in support of the null.

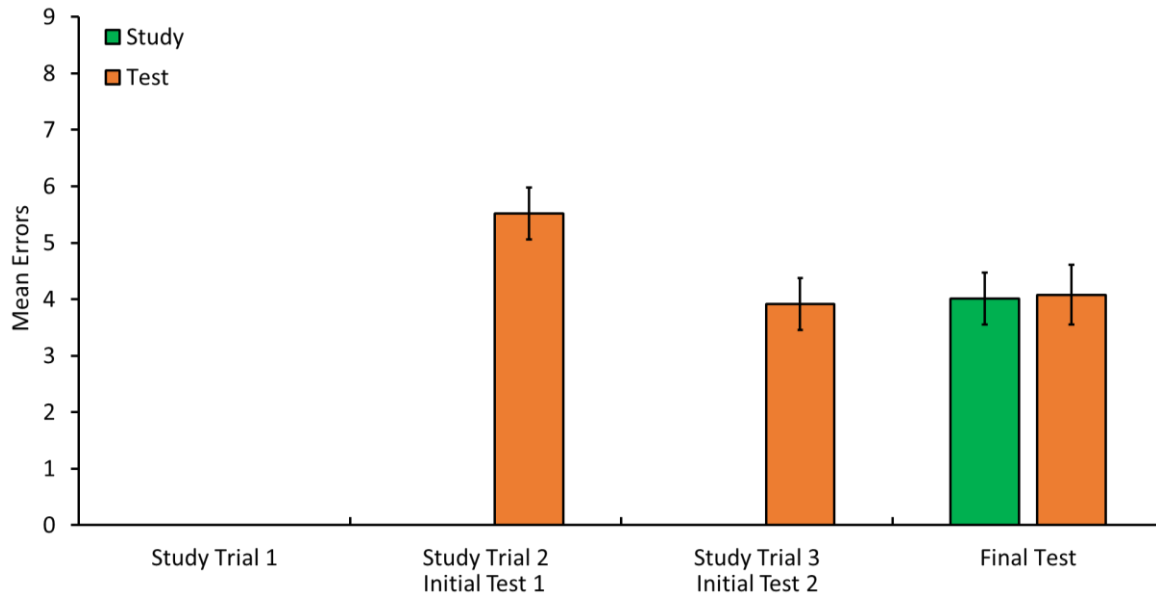


Figure 17. Mean total errors in Experiment 3 for participants in the Study and Test conditions across learning trials and at final test. Error bars represent ± 1 SEM. Mean errors were always zero on study trials during learning.

Exploratory analyses were conducted on errors by evaluating 1) whether any errors produced at final test occurred on initial test 1 or initial test 2, and 2) whether any errors produced during an initial test occurred on subsequent tests (or at final test). Errors produced in the test condition were coded as the following: 1) repeated location, same turn direction, 2) repeated location, different turn direction, 3) did not repeat, or 4) new errors. Note that a similar analysis with the study condition are not possible, because study participants were always guided during learning and therefore did not make any errors.

First, of the total proportion of errors at final test in Experiment 2 (Figure 18, left bar), approximately 57 percent were “repeated location, same turn direction” errors that occurred either at initial test 1 or initial test 2. Second, seven percent of errors produced at final test were

“repeated location, different turn direction” in either initial test 1 or initial test 2. Lastly, 35 percent of errors at final test were “new errors” that did not occur in either initial test 1 or initial test 2.

In Experiment 3 (Figure 18, right bar), a similar pattern was found. Of the proportion of errors at final test, 73 percent of errors were “repeated location, same turn direction”.

Approximately nine percent of the errors at final test were “repeated location, different turn direction” and lastly, 18 percent of errors at final test were “new errors” that did not occur in either initial tests. Overall in Experiments 2 and 3, a large proportion (at least over 50 percent) of final test errors that were repeated occurred at initial test 1 or initial test 2. Additional analyses were conducted to examine what proportion of errors produced during learning also occurred from an initial test to subsequent tests (i.e., initial test 1 to initial test 2) and at final test (i.e., initial test 2 to final test).

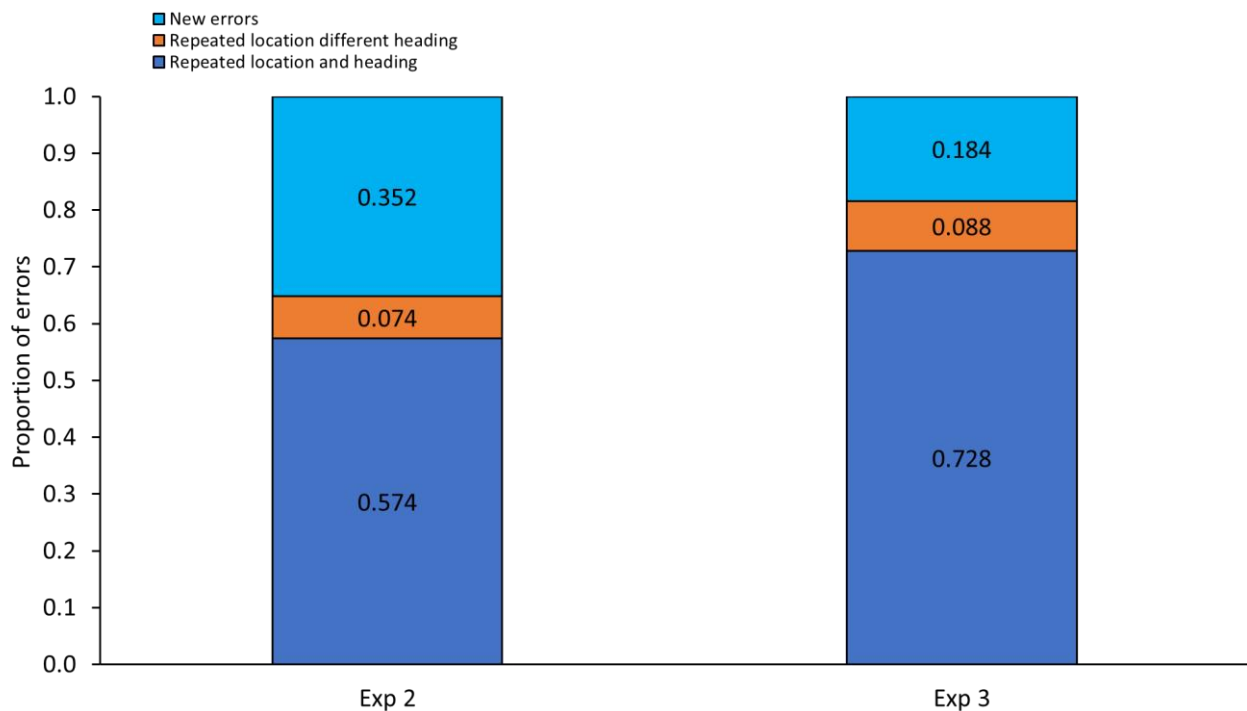


Figure 18. The stacked bars represent the proportion errors for the different types of final test errors in the test condition. This represents whether errors at final test occurred at initial test 1 or initial test 2 for Experiments 2 and 3. This also includes new errors that were produced at final test but that did not occur during initial tests 1 or initial test 2.

Errors produced from initial test 1 to initial test 2, and initial test 2 to final test were calculated to observe patterns of errors produced throughout learning and at final test for both Experiments 2 and 3. In Experiment 2, from initial test 1 to initial test 2 (Figure 19, left bar), approximately 31 percent of errors produced were “repeated location, same turn direction.” Four percent of errors from initial test 1 to initial test 2 were “repeated location, different turn direction.” Lastly, approximately 65 percent of errors produced at initial test 1 “did not repeat” to initial test 2. This pattern shifts slightly when exploring what proportion of errors produced at initial test 2 occurred at final test (Figure 19, right bar). Although a similar pattern is observed, the proportion of errors produced during initial test 2 to final test were larger for “repeated location, same turn direction” errors. A similar pattern for “repeated location, different turn direction” was observed, accounting for approximately eight percent of errors, and lastly, approximately 40 percent of errors were “did not repeat” errors.

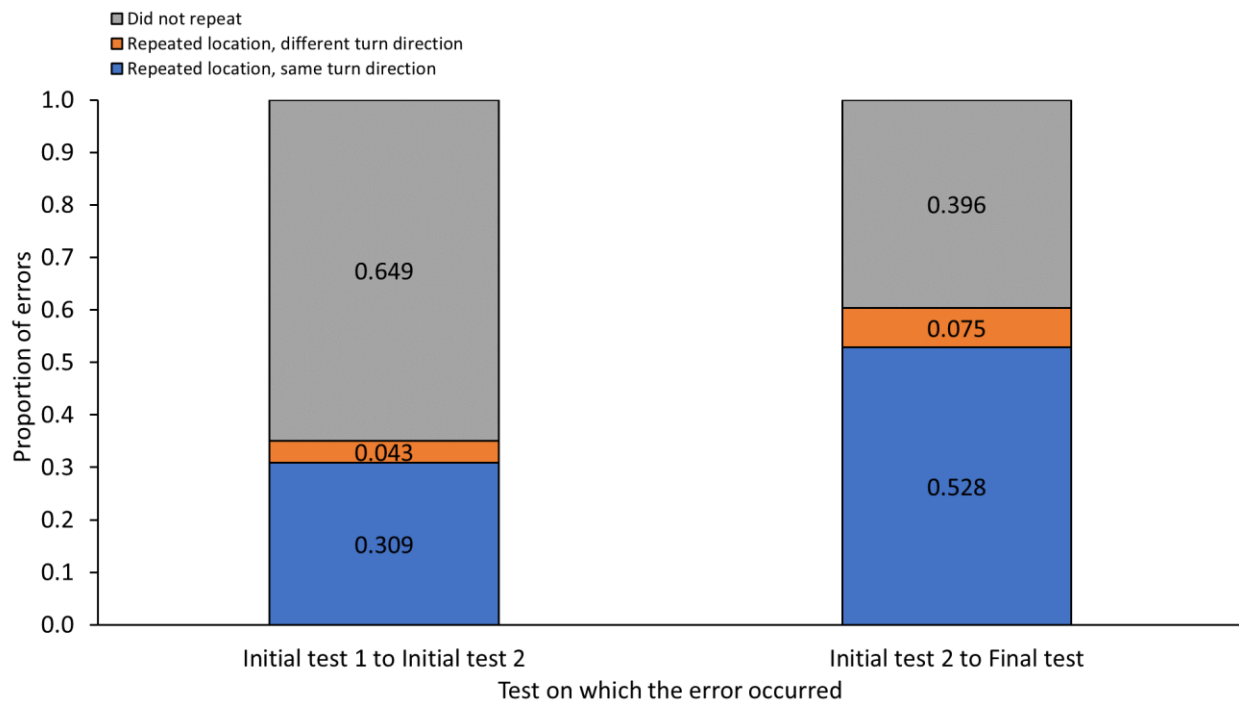


Figure 19. For Experiment 2, the stacked bars represent the proportion of the types of errors that persisted from initial test 1 to initial test 2 (left bar), and from initial test 2 to final test (right bar) for Experiment 2.

For Experiment 3 (Figure 20), the same analysis was conducted to examine patterns of observed errors between initial test 1 and initial test 2, and initial test 2 to final test. Of the errors from initial test 1 to initial test 2 (Figure 20, left bar), approximately 44 percent of errors were “repeated location, same turn direction,” with seven percent as “repeated location, different turn direction,” and 49 percent were “did not repeat” errors. For errors from initial test 2 to final test (Figure 20, right bar), 57 percent of errors were “repeated location, same turn direction,” with four percent “repeated location, different turn direction,” and 39 percent were “did not repeat” errors.

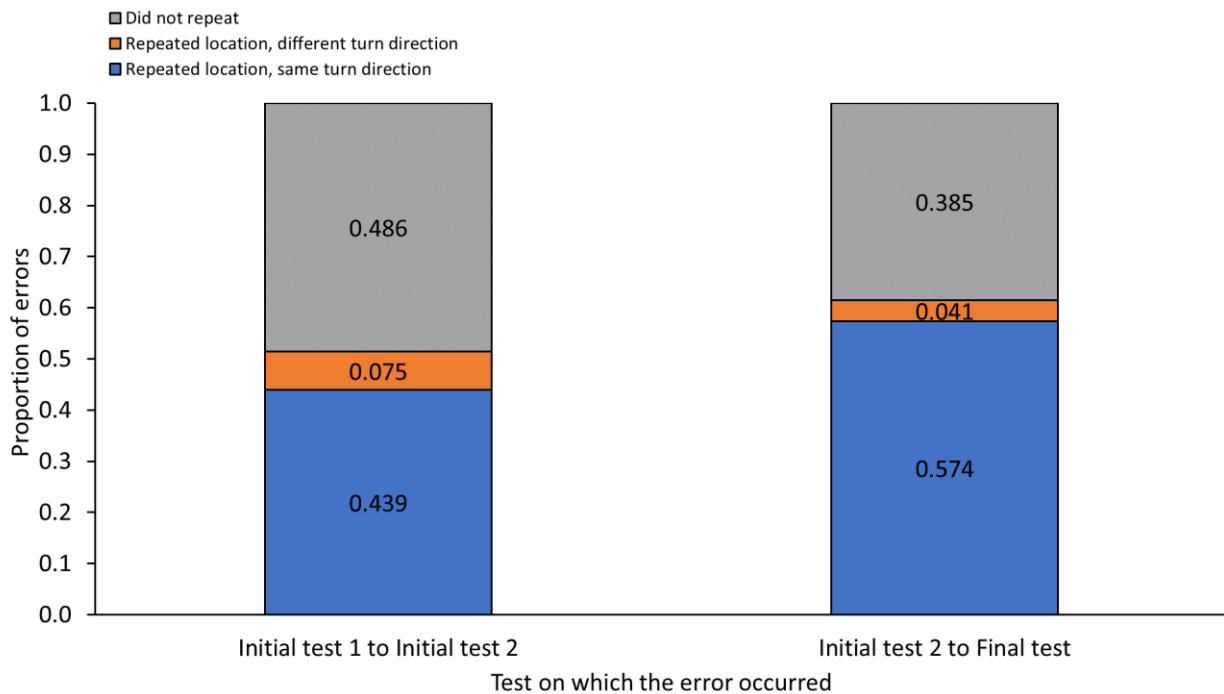


Figure 20. For Experiment 2, the stacked bars represent the proportion of the types of errors that persisted from initial test 1 to initial test 2 (left bar), and from initial test 2 to final test (right bar) for Experiment 3.

Discussion: Experiments 2 and 3

In the present study, testing with corrective feedback was not helpful for route learning as predicted beyond using GPS route guidance. Several possible explanations for why Experiments 2 and 3 did not find a benefit of testing in relation to the data and evidence from other studies

will be discussed here. When participants in the test condition produced an error during learning (i.e., initial tests), the effect of testing plus corrective feedback was not effective enough to reliably show a positive testing effect at final test. This is evidenced in the exploratory analyses with the different types of repeated errors (see Figure 19, 20, 21). Similar patterns can be observed which reveals a large proportion of errors produced during initial tests 1 to initial test 2, and initial test 2 to final test. This was especially true for errors repeated at the same location and same turn direction. In the study by Kelly, Carpenter, and Sjolund (2015), a reverse testing effect was observed in two of the experiments when movement errors were not prevented before corrective feedback was provided. No data was reported in that study to compare whether errors produced during learning were also repeated at final test. However, it is possible when movement errors were not prevented during learning, errors persisted at final test.

Another explanation for why participants perseverated in repeating errors during initial tests and at final test is related to stimulus-response associations which involves learning a sequence of motor responses (e.g., turn left) at specific locations (e.g., at the corner of the café). It is argued that stimulus-response learning relies on the caudate nucleus, a brain region also known to support tasks (e.g., learning how to drive) that tap into procedural learning (i.e., “habit learning”) (Squire & Zola, 1996). Route knowledge is argued to be procedural in nature, which consists of actions associated with decision points (Golledge, 1991) and with that, there is evidence to suggest that route learning is supported by the caudate nucleus while survey learning is supported in the hippocampus (Hartley, Maguire, Spiers, & Burgess, 2003; Maguire et al., 2000). This relationship could explain why past studies have demonstrated not only a benefit of testing for verbal materials, but also for nonverbal materials specific to map learning (Carpenter & Pashler, 2007), spatial memory for an array of objects (Carpenter & Kelly, 2012), and near

transfer of map learning (Brunye et al., 2019), all of which are mediated by the hippocampus. This also likely explains why route learning may not benefit from testing in the same way that map learning does because the underlying mechanisms that support both route learning are mediated by the striatum and the caudate nucleus.

Why were errors so resistant to feedback? One possible connection is research on errorless learning, which has found that acquiring new procedural (motor) skills benefits from progressing from easier tasks to more difficult ones. For example, a study found that performance on a golf putting task was best when an “errorless learning” condition began with easier putts and became increasingly more difficult compared to an “errorful learning” condition that started with more difficult putts and became progressively easier (Maxwell, Kerr, & Weedon, 2001). One reason being that producing errors on a novel motor task likely influences the adoption of an explicit learning mode until the skill becomes automated to adopting an implicit learning mode. Explicit learning modes are typically activated during early stages of learning on tasks that require motor skills because the person is likely making intuitive (explicit) decisions to perform the task successfully while attempting to avoid unsuccessful attempts. That said, when motor tasks begin with easier successful attempts before it becomes progressively more difficult, implicit learning modes are likely activated because the performer is less likely to identify crucial aspects of skilled performance and this leads to passive aggregation of task-relevant information, thus leading to a larger knowledge base. On the other hand, if repeatedly following route guidance is akin to information automation, perhaps there are unintended consequences with skill degradation. In other domains such as aviation, avoiding errors is critical for reducing fatal incidents. Pilots are often presented with multiple sources of information (both auditory and visual) in the cockpit, and therefore the pilot’s senses can become overloaded

(Stokes & Wickens, 1988). As flight dashboards become increasingly more complex, information automation is critical for reducing cognitive workload. However, such automation may come at a cost with greater skill degradation than manual practice over time even if “errorful learning” occurs (Volz, Yang, Dudley, Lynch, Dropps, & Dorneich, 2016).

In the case of learning a novel route in during initial tests, if the driver accrues several incorrect turns, it is likely that an explicit learning mode was adopted (e.g., “I think I have to turn right at this intersection. No, that was the incorrect turn. I was supposed to continue straight at that intersection and turn left at the café. I’ll have to remember not to do that again. Rats, I made another incorrect turn!”). Likewise, with golf putting, if the novice performs a putt unsuccessfully, they are likely verbalizing rules to avoid unsuccessful attempts on subsequent trials (e.g., correcting their posture, improving their grip, properly coordinating their swing, etc.) and this explicit process with motor skills often leads to small performance benefits. Therefore, route learning may continue to benefit from memory retrieval of routes if attempts at errorless learning (or implicit learning modes) occur in the same way that participants benefited from when movement errors were prevented with corrective feedback (Kelly, Carpenter, & Sjolund, 2015).

From the perspective of learning and memory research, multiple-choice tests (e.g., four-choice alternative, or true/false tests) could be analogous to a four-way intersection with three possible choices (e.g., continue straight, turn left, or turn right) but perhaps to a lesser extent due to the procedural nature of the task. Nonetheless, the navigator is engaged with a forced recall-like test which occurs for every decision point that is encountered along a novel route. One possible explanation rooted in memory research (Roediger & Marsh, 2005; Marsh, Roediger, Bjork, & Bjork, 2007) found that using multiple choice tests where one or multiple correct

answers exist exposes the subject to incorrect answers which may seem correct at later recall. This effect of familiarity with the incorrect answer (i.e., lures) is likely to be repeated at final test if that same incorrect answer was produced during learning. While a positive testing effect still occurs overall compared to restudy conditions, multiple choice tests also produce opposing effects that lead the learner to encode false knowledge when exposed to incorrect answers. More precisely, Marsh et al. (2007) found that if students answered a final cued recall question with an incorrect answer, a lure they had read from previous test trials, the same error was more likely to be repeated at final test. It was also suggested that if the student produced a correct answer during initial tests, they were not likely to select the incorrect answer for that same item at final test. In the case of Experiments 2 and 3, one interpretation is that for every critical decision point, only one correct directional turn exists while other choices are lures. At final test, the same lures are encountered and do not change between initial test trials, and therefore if an incorrect turn (i.e., lure) was produced during initial tests, then the same errors were likely repeated because the same incorrect lure that was chosen is presented at final test. Unlike educational materials, lures can be manipulated between multiple initial test trials, but lures at intersections cannot. Therefore, the effect of familiarity could produce this negative testing effect whereby errors produced during learning also persist at final test.

Perhaps the benefits of testing would be seen in subsequent trials beyond two initial tests. However, in Experiments 2 and 3, two initial test trials were not enough to demonstrate a boost in route learning beyond restudying (i.e., using route guidance) on the final test after a two-day delay. Ultimately, under these conditions, testing provided no benefit to learning a route than GPS route guidance.

CHAPTER 4. DISCUSSION AND CONCLUSION

Spatial navigation is a core cognitive ability in humans and is essential for everyday tasks such as navigating to and from work, remembering where you parked your vehicle after shopping at the mall, finding your way around in an unfamiliar city using GPS wayfinding, and providing directions by pointing to unseen landmarks. These everyday examples highlight how pervasive spatial navigation is and the intersection between spatial learning and technology has become an emerging topic in spatial cognitive research. This chapter will address theoretical and applied considerations, limitations, and future research.

Theoretical and Applied implications: Experiment 1

An emerging problem for everyday VR consumers is the limited tracked physical space required to naturally walk and turn in large-scale VEs. Therefore, VR designers have developed alternative locomotion methods, but research suggests that these methods are not without spatial cognitive costs. Other work has found support that rotational self-motion cues associated with partially concordant teleporting leads to better spatial updating performance than discordant teleporting (Cherep et al., 2020; Kelly et al., 2020). However, there is less agreement on whether rotational self-motion cues actually lead to better survey knowledge acquisition (Huffman & Ekstrom, 2019b; Li & Giudice, 2013; Mellet, Laou, Petit, Zago, Mazoyer, & Tzourio-Mazoyer, 2010; Waller, Loomis, & Steck, 2003). Using two common measures of survey knowledge (i.e., pointing to relative directions of objects and map drawings), Experiment 1 provides strong evidence, adding to the growing picture that access to rotational self-motion cues with partially concordant teleporting leads to more accurate survey representations of large-scale VEs than discordant teleporting.

Relatedly, another emerging area in applied research is the evaluation of advanced hardware in support of creating more immersive VR experiences. Because navigation such as walking in VR is limited by the tracked physical space, omni-directional treadmills have become of interest because they afford users the ability to walk freely simulating a “natural” walking gait to traverse through large-scale VEs, but its high cost make its use prohibitive for VR consumers. Users on omni-directional treadmills are typically harnessed at the waist to keep the user centered while the user walks on small frictionless circular platform allowing the user to walk in any direction in the VE.

However, such hardware presents new questions and challenges to understand not only whether the fidelity of the user experience resembles natural walking, but it also presents new ways to explore how a variety of real-world contexts (e.g., navigation training in complex environments, vastness of large-scale environments, environmental cues or lack thereof) simulated in VR can exert influence on spatial learning. In Experiment 1, there was clear evidence that rotational self-motion cues led to more accurate survey knowledge acquisition. However, a missing piece to this area of research is whether full walking with accompanying body-based cues and visual self-motion would produce equally accurate or more accurate survey representations compared to rotational self-motion cues alone. One way to further investigate this is to replicate Experiment 1 with a full walking condition and full walking on an omni-directional treadmill. This thrust of research not only has applied implications, but also theoretical contributions for understanding which body-based cues contribute to accurate survey knowledge acquisition. Most of the research on omni-directional treadmills has primarily been focused on conducting usability studies to evaluate the user experience on subjective measures

such as presence and immersion (Calandra, Lamberti, & Migliorini, 2019; Dębska, Polechoński, Mynarski, & Polechoński, 2019).

Future Research: Experiment 1

Future directions in research should expand on Experiment 1, by evaluating whether omni-directional treadmills produce equal or worse performance in spatial learning compared to real-walking or other commonly used locomotion interfaces (e.g., walking in place, teleporting). To conduct such as experiment would require several different conditions: 1) full walking with all self-motion cues (VR HMDs such as the Oculus Quest allow users to walk freely untethered), 2) omni-directional treadmill walking condition with all self-motion cues, 3) a rotation-only condition whereby the participant has access to rotational self-motion cues, but uses a joystick for translational movement, and 4) a joystick-only condition with only visual self-motion but no body-based cues associated with movement of the body and movement in the VE. One nuance with omni-directional treadmills is whether visual self-motion in the VE matches 1:1 with movement of the body. For example, a user could walk the equivalent of 10 feet by stepping on the treadmill and move 20 feet in the VE (i.e., a 2:1 ratio). Therefore, increasing the gain could be another condition. Like Experiment 1, participants could be assigned to one of the locomotion interfaces and instructed to explore and learn the locations of several different objects in a large-scale VE. After learning, participants can perform an object-to-object pointing task and a map drawing task.

Cybersickness is another avenue that has sought the attention of VR designers and researchers alike. Symptoms associated with cybersickness often occur when there is conflict between visual self-motion cues from the VE and body-based self-motion cues (e.g., receiving smooth visual input in the HMD while physically seated in a chair). This is the very motivation

for why VR designers developed teleporting as a locomotion interface, since teleporting eliminates visual motion. However, very little research has evaluated its influence on acquiring different spatial properties, hence the motivation for conducting Experiment 1. Omni-directional treadmills have gained interest among the VR and research circles, and it has been speculated that it might be one solution in reducing symptoms related to cybersickness because it presumably resembles real-walking. Whether such a device would actually reduce cybersickness is unclear because there is no empirical data to support this prediction. In addition, measures of cybersickness such as the Simulator Sickness Questionnaire (Kennedy, Berbaum, & Lilienthal, 1993; Stanney, Kennedy, & Drexler, 1997; Stone, 2017) have been met with some scrutiny not only because of its lack of objectivity, but because it was originally designed for pilots who experience simulator sickness in flight simulators.

From a theoretical perspective, in reference to Montello's (1998) framework regarding multiple types of spatial knowledge, more work needs to be done to understand how different spatial properties are acquired as one begins to explore a novel environment. For example, some evidence suggests that individuals can acquire route knowledge and survey knowledge simultaneously at different rates with little exposure to an environment (e.g., Montello & Pick, 1993), but the precise rate of acquisition is not clear. Such an investigation is difficult to conduct in the real-world without experimental control and standardization across studies. Therefore, omni-directional treadmills and modern VR HMDs that allow unrestricted movement could be a vital tool for exploring these questions.

Another area of research that requires further exploration is the relationship between the acquisition of these different types of spatial properties and other factors such as individual differences in spatial ability (Cherep, Lim, Kelly, Miller, & Gilbert, 2020; Newcombe, 2018;

Weisberg et al., 2014) which contributes to a lot of the variability observed in spatial learning tasks, or other factors such as environmental complexity (Carlson, Hölscher, Shipley, & Dalton, 2010; Haq & Zimring, 2003) or vastness of environments (Rauhoeft, Leyrer, Thompson, Stefanucci, Klatzky, & Mohler, 2015). Further exploration in spatial learning in contexts that resemble real-world circumstances would provide a more complete picture in understanding the underlying spatial cognitive processes that contribute to our ability to perceive, remember, and navigate through space.

Theoretical and Applied Implications: Experiments 2 and 3

As of 2019, approximately 81 percent of Americans own a smartphone device and this number is likely to increase over the next decade (Pew Research, 2019). Presumably, this growth in smartphone ownership may lead to an increase use in mobile-based GPS wayfinding because of the ease in access. The benefits of wayfinding efficiency likely outweigh the costs of getting lost in the short-term, but the spatial skills that would normally be acquired through direct experience without a GPS device could diminish with long-term effects (Dahmani & Bohbot, 2020) Hejtmánek, et al., 2018; Ruginski, Creem-Regeher, Stefanucci, & Cashdan, 2019). One concern about GPS use is whether repeated following of route guidance reduces memory retrieval, which could result in poorer route memory. However, Experiments 2 and 3 provide strong evidence that GPS route guidance did not lead to poorer route knowledge compared to retrieving a route from memory. This suggests that using retrieval during navigation may lead to errors which then may be detrimental to learning.

Though the positive effects of testing did not surface in the context of learning a novel route, such results add to the growing body of research on errorless learning with motor skill acquisition (e.g., Maxwell et al., 2001) and the negative effects of testing (Marsh, Roediger,

Bjork, & Bjork, 2007; Roediger & Marsh, 2005). Though, testing typically produces reliable and robust positive effects in various learning paradigms and educational contexts (Rowland, 2014), but primarily with verbal materials. However, such positive effects are not clearly seen with nonverbal materials in the spatial cognitive domain and this study accomplishes that by exploring boundary conditions of testing.

Future Research: Experiments 2 and 3

The intersection between technology and spatial learning should be further explored to not only understand the negative consequences of relying on such wayfinding devices, but to also explore ways that technology can be leveraged to improve spatial learning. For example, superimposing turn-by-turn directions displayed on the windshield of vehicles may help to reduce splitting the driver's attention because of the cognitive distance between the driver's eyes and typical placement of GPS device in a vehicle such as the center radio console or on the center overhead dash (Kim & Dey, 2009). GPS tracking out in the open is fairly accurate to within three meters of pinpoint accuracy, but orientation specific tracking is rather crude and can sometimes be problematic for navigators to know which direction to turn if their current heading is not accurately tracked. To resolve this, Google deployed a feature on smartphones called Google Maps AR that allow navigators to use their camera application and scan their surrounding environment in real-time, and superimposes the correct directional heading on the smartphone device to reorient the navigator relative to their position on a map. Navigators who have diminished spatial abilities or older adults who suffer from spatial navigation deficits due to cognitive decline may rely heavily on such navigational aids. However, reliance on such aids reduces our need to rely on our spatial knowledge which could lead to negative short- and long-term effects on our overall spatial skills. For example, the new Google Maps feature may

diminish the need to rely on global landmarks or geometric cues which can be used to as reorienting cue in space (Lee & Spelke, 2010; Nardini, Marko, Peter Jones, Bedford, & Braddick, 2008).

It would not be practical to test yourself at an intersection before making a turn, but verbal interactions from a GPS device that engages retrieval practice in an errorless-like (implicit learning mode) strategy on novel routes could be beneficial for long-term retention. For example, a newly learned route may require seven directional turns to arrive at the destination. Verbal interactions from the GPS device could probe the driver to retrieve the first directional turn presuming the first directional turn is the easiest to recall and provide route guidance for the remainder of the route. The next time the route is repeated, the driver could retrieve the next two directional turns and so on. Based on the errorless learning literature (e.g., Maxwell et al. 2001) this approach would be less likely to activate an explicit learning mode. However, such interactions could raise concerns for dividing a driver's attention in real-world contexts.

Conclusion

This work has not only applied considerations, but also theoretical implications for understanding the intersection between technologies and spatial cognitive processes. Other existing frameworks (e.g., Carlson, Hölscher, Shipley, & Dalton, 2010; Montello, 1998) encompass factors and intersections such as the acquisition of multiple types of spatial knowledge, strategies and spatial abilities, the spatial structure of buildings, or survey knowledge that navigators develop as they navigate. Considering the relationship that humans have with technology, to date there is no existing framework that integrates the intersection between prevailing technologies and spatial learning. Such a framework would be helpful to develop applications that not only enhance spatial learning, but also to understand why certain

technologies impair spatial learning. This dissertation work contributes novel findings from three experiments with the goal of supplementing future work in developing a novel integrative framework that intersects between technology and spatial learning.

REFERENCES

- Al Zayer, M., MacNeilage, P., & Folmer, E. (2018). Virtual locomotion: a survey. *IEEE transactions on visualization and computer graphics*.
- Aoki, H., Oman, C. M., & Natapoff, A. (2007). Virtual-reality-based 3D navigation training for emergency egress from spacecraft. *Aviation, space, and environmental medicine*, 78(8), 774-783.
- Beard, S. (2019, May). London tax drivers hail “The Knowledge”. *Marketplace*.
<https://www.marketplace.org/2019/05/14/london-taxi-drivers-hail-the-knowledge/>
- Bergasa, L. M., Almería, D., Almazán, J., Yebes, J. J., & Arroyo, R. (2014, June). Drivesafe: An app for alerting inattentive drivers and scoring driving behaviors. In *2014 IEEE Intelligent Vehicles symposium proceedings* (pp. 240-245). IEEE.
- Bliss, J. P., Tidwell, P. D., & Guest, M. A. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence: Teleoperators & Virtual Environments*, 6(1), 73-86.
- Bond, M. (2020). From here to there: The art and science of finding and losing our way. The Belknap Press of Harvard University Press.
- Bowman, D. A., Koller, D., & Hodges, L. F. (1997, March). Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality* (pp. 45-52). IEEE.
- Bozgeyikli, E., Raij, A., Katkooori, S., & Dubey, R. (2016, October). Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play* (pp. 205-216).
- Brunyé, T. T., Smith, A. M., Hendel, D., Gardony, A. L., Martis, S. B., & Taylor, H. A. (2020). Retrieval practice enhances near but not far transfer of spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 46(1), 24.
- Butler, A. C. (2010). Repeated testing produces superior transfer of learning relative to repeated studying. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36(5), 1118.
- Calandra, D., Lamberti, F., & Migliorini, M. (2019, September). On the Usability of Consumer Locomotion Techniques in Serious Games: Comparing Arm Swinging, Treadmills and Walk-in-Place. In *2019 IEEE 9th International Conference on Consumer Electronics (ICCE-Berlin)* (pp. 348-352). IEEE.
- Carlson, L. A., Hölscher, C., Shipley, T. F., & Dalton, R. C. (2010). Getting lost in buildings. *Current Directions in Psychological Science*, 19(5), 284-289.

- Carpenter, S. K. (2009). Cue strength as a moderator of the testing effect: the benefits of elaborative retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(6), 1563.
- Carpenter, S. K., & DeLosh, E. L. (2006). Impoverished cue support enhances subsequent retention: Support for the elaborative retrieval explanation of the testing effect. *Memory & cognition*, 34(2), 268-276.
- Carpenter, S. K., & Kelly, J. W. (2012). Tests enhance retention and transfer of spatial learning. *Psychonomic Bulletin & Review*, 19(3), 443-448.
- Carpenter, S. K., & Pashler, H. (2007). Testing beyond words: Using tests to enhance visuospatial map learning. *Psychonomic Bulletin & Review*, 14(3), 474-478.
- Carrier, M., & Pashler, H. (1992). The influence of retrieval on retention. *Memory & Cognition*, 20(6), 633-642.
- Chance, S. S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998). Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence*, 7(2), 168-178.
- Cherep, L. A., Lim, A. F., Kelly, J. W., Acharya, D., Velasco, A., Bustamante, E., ... & Gilbert, S. B. (2020). Spatial cognitive implications of teleporting through virtual environments. *Journal of Experimental Psychology: Applied*.
- Cherep, L. A., Lim, A. F., Kelly, J. W., Miller, A., & Gilbert, S. B. (2020, March). Individual differences in teleporting through virtual environments: A latent profile analysis. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 725-726). IEEE.
- Chirico, A., Yaden, D. B., Riva, G., & Gaggioli, A. (2016). The potential of virtual reality for the investigation of awe. *Frontiers in psychology*, 7, 1766.
- Chrastil, E. R., & Warren, W. H. (2013). Active and passive spatial learning in human navigation: Acquisition of survey knowledge. *Journal of experimental psychology: learning, memory, and cognition*, 39(5), 1520.
- Chrastil, E. R., & Warren, W. H. (2015). Active and passive spatial learning in human navigation: Acquisition of graph knowledge. *Journal of experimental psychology: learning, memory, and cognition*, 41(4), 1162.
- Christou, C. G., & Aristidou, P. (2017, June). Steering versus teleport locomotion for head mounted displays. In *International Conference on Augmented Reality, Virtual Reality and Computer Graphics* (pp. 431-446). Springer, Cham.

- Cushman, L. A., Stein, K., & Duffy, C. J. (2008). Detecting navigational deficits in cognitive aging and Alzheimer disease using virtual reality. *Neurology*, *71*(12), 888-895.
- Dahmani, L., & Bohbot, V. D. (2020). Habitual use of GPS negatively impacts spatial memory during self-guided navigation. *Scientific reports*, *10*(1), 1-14.
- Dębska, M., Polechoński, J., Mynarski, A., & Polechoński, P. (2019). Assessment of enjoyment and intensity of physical activity in immersive virtual reality on the omni-directional omni treadmill and icaros flight simulator in the context of recommendations for health. *Int. J. Environ. Res. Public Health*, *16*, 3673. DOI: 10.3390/ijerph16193673
- Delacre, M., Lakens, D., & Leys, C. (2017). Why psychologists should by default use Welch's t-test instead of Student's t-test. *International Review of Social Psychology*, *30*(1).
- Diersch, N., & Wolbers, T. (2019). The potential of virtual reality for spatial navigation research across the adult lifespan. *Journal of Experimental Biology*, *222*(Suppl 1).
- Fenech, E. P., Drews, F. A., & Bakdash, J. Z. (2010, September). The effects of acoustic turn-by-turn navigation on wayfinding. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 54, No. 23, pp. 1926-1930). Sage CA: Los Angeles, CA: SAGE Publications.
- Friedman, A., & Kohler, B. (2003). Bidimensional regression: Assessing the configural similarity and accuracy of cognitive maps and other two-dimensional data sets. *Psychological methods*, *8*(4), 468.
- Gallistel, C. R. (2009). The importance of proving the null. *Psychological review*, *116*(2), 439.
- Gardony, A. L., Brunyé, T. T., Mahoney, C. R., & Taylor, H. A. (2013). How navigational aids impair spatial memory: Evidence for divided attention. *Spatial Cognition & Computation*, *13*(4), 319-350.
- Gardony, A. L., Taylor, H. A., & Brunyé, T. T. (2016). Gardony Map Drawing Analyzer: Software for quantitative analysis of sketch maps. *Behavior research methods*, *48*(1), 151-177.
- Grant, S. C., & Magee, L. E. (1998). Contributions of proprioception to navigation in virtual environments. *Human Factors*, *40*(3), 489-497.
- Haq, S., & Zimring, C. (2003). Just down the road a piece: The development of topological knowledge of building layouts. *Environment and behavior*, *35*(1), 132-160.
- Hartley, T., Maguire, E. A., Spiers, H. J., & Burgess, N. (2003). The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. *Neuron*, *37*(5), 877-888.

- He, Q., McNamara, T. P., Bodenheimer, B., & Klippel, A. (2019). Acquisition and transfer of spatial knowledge during wayfinding. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 45(8), 1364.
- Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, 34(2), 151-176.
- Hejtmánek, L., Oravcová, I., Motýl, J., Horáček, J., & Fajnerová, I. (2018). Spatial knowledge impairment after GPS guided navigation: Eye-tracking study in a virtual town. *International Journal of Human-Computer Studies*, 116, 15-24.
- Hodgson, E., Bachmann, E., & Waller, D. (2011). Redirected walking to explore virtual environments: Assessing the potential for spatial interference. *ACM Transactions on Applied Perception (TAP)*, 8(4), 22.
- Hölscher, C., Brösamle, M., & Vrachliotis, G. (2012). Challenges in multilevel wayfinding: A case study with the space syntax technique. *Environment and Planning B: Planning and Design*, 39(1), 63-82.
- Huffman, D. J., & Ekstrom, A. D. (2019a). A Modality-Independent Network Underlies the Retrieval of Large-Scale Spatial Environments in the Human Brain. *Neuron*, 104(3), 611-622.
- Huffman, D. J., & Ekstrom, A. D. (2019b). Which way is the bookstore? A closer look at the judgments of relative directions task. *Spatial Cognition & Computation*, 19(2), 93-129.
- Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive psychology*, 52(2), 93-129.
- Kelly, J. W., Carpenter, S. K., & Sjolund, L. A. (2015). Retrieval enhances route knowledge acquisition, but only when movement errors are prevented. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(5), 1540.
- Kelly, J. W., Cherep, L. A., & Siegel, Z. D. (2017). Perceived space in the HTC Vive. *ACM Transactions on Applied Perception (TAP)*, 15(1), 1-16.
- Kelly, J. W., Ostrander, A., Lim, A. F., Cherep, L. A., & Gilbert, S.B. (2020). Teleporting through virtual environments: Effects of path scale and environment scale on spatial updating. *IEEE: Transactions on Visualization and Computer Graphics*.
- Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3), 203-220.

- Kessels, R. P., van Loon, E., & Wester, A. J. (2007). Route learning in amnesia: a comparison of trial-and-error and errorless learning in patients with the Korsakoff syndrome. *Clinical Rehabilitation*, 21(10), 905-911.
- Kim, S., & Dey, A. K. (2009, April). Simulated augmented reality windshield display as a cognitive mapping aid for elder driver navigation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 133-142).
- Klatzky, R. L., Loomis, J. M., Beall, A. C., Chance, S. S., & Golledge, R. G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological science*, 9(4), 293-298.
- Kornell, N., Hays, M. J., & Bjork, R. A. (2009). Unsuccessful retrieval attempts enhance subsequent learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(4), 989.
- Kornell, N., & Vaughn, K. E. (2016). How retrieval attempts affect learning: A review and synthesis. In *Psychology of learning and motivation* (Vol. 65, pp. 183-215). Academic Press.
- Langbehn, E., Lubos, P., & Steinicke, F. (2018, April). Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. In *Proceedings of the Virtual Reality International Conference-Laval Virtual* (pp. 1-9).
- Lee, S. A., & Spelke, E. S. (2010). Two systems of spatial representation underlying navigation. *Experimental brain research*, 206(2), 179-188.
- Lester, A. W., Moffat, S. D., Wiener, J. M., Barnes, C. A., & Wolbers, T. (2017). The aging navigational system. *Neuron*, 95(5), 1019-1035.
- Li, H., & Giudice, N. A. (2013, November). The effects of immersion and body-based rotation on learning multi-level indoor virtual environments. In *Proceedings of the Fifth ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 8-15). ACM.
- Lin, A. Y., Kuehl, K., Schöning, J., & Hecht, B. (2017, May). Understanding "Death by GPS" A Systematic Study of Catastrophic Incidents Associated with Personal Navigation Technologies. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 1154-1166).
- Liu, S. (2019, August). *Global consumer virtual reality market size 2016-2022*. Statista. <https://www.statista.com/statistics/528779/virtual-reality-market-size-worldwide/>
- Loomis, J. M., Klatzky, R. L., Golledge, R. G., & Philbeck, J. W. (1999). Human navigation by path integration. In R. G. Golledge (Ed.), *Wayfinding: Cognitive mapping and other spatial processes* (pp. 125-151). Baltimore: Johns Hopkins.

- Loomis, J. M. & Knapp, J. M. (2004). Visual perception of egocentric distance in real and virtual environments. In *Virtual and Adaptive Environments*, L. J. Hettinger and M. W. Haas (Eds.). Erlbaum, Mahwah, NJ, 21–46.
- Loup, G., & Loup-Escande, E. (2019). Effects of travel modes on performances and user comfort: a comparison between ArmSwinger and teleporting. *International Journal of Human–Computer Interaction*, 35(14), 1270-1278.
- MacKay, D. B. (1976). The effect of spatial stimuli on the estimation of cognitive maps. *Geographical Analysis*, 8(4), 439-452.
- Mainelli, T., Shirer, M. & Ubrani, J. (2019, March). Augmented reality and virtual reality headsets poised for significant growth. *International Data Corporation*. Retrieved from <https://www.idc.com/getdoc.jsp?containerId=prUS44966319>
- Maguire, E.A., Gadian, D.G., Johnsruce, I.S., Good, C.D., Ashburner, J., Frackowiak, R.S.J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, 97, 4398-4403. doi:10.1073/pnas.070039597
- Marsh, E. J., Roediger, H. L., Bjork, R. A., & Bjork, E. L. (2007). The memorial consequences of multiple-choice testing. *Psychonomic Bulletin & Review*, 14(2), 194-199.
- McNamara, T. P., & Diwadkar, V. A. (1997). Symmetry and asymmetry of human spatial memory. *Cognitive Psychology*, 34(2), 160-190.
- Mellet, E., Laou, L., Petit, L., Zago, L., Mazoyer, B., & Tzourio-Mazoyer, N. (2010). Impact of the virtual reality on the neural representation of an environment. *Human brain mapping*, 31(7), 1065-1075.
- Moghadam, K. R., Banigan, C., & Ragan, E. D. (2018). Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness. *IEEE transactions on visualization and computer graphics*.
- Montello, D. R. (1993, September). Scale and multiple psychologies of space. In *European conference on spatial information theory* (pp. 312-321). Springer, Berlin, Heidelberg.
- Montello, D. R. (1998). A new framework for understanding the acquisition of spatial knowledge in large-scale environments. *Spatial and temporal reasoning in geographic information systems*, 143-154.
- Montello, D. R., & Pick Jr, H. L. (1993). Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior*, 25(3), 457-484.

- Montenegro, J. M. F., & Argyriou, V. (2017). Cognitive evaluation for the diagnosis of Alzheimer's disease based on turing test and virtual environments. *Physiology & behavior*, 173, 42-51.
- Moser, B. K., & Stevens, G. R. (1992). Homogeneity of variance in the two-sample means test. *The American Statistician*, 46(1), 19-21.
- Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current biology*, 18(9), 689-693.
- Newcombe, N. S. (2018). Individual variation in human navigation. *Current Biology*, 28(17), R1004-R1008.
- O'keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford: Clarendon Press.
- Padilla, L. M., Creem-Regehr, S. H., Stefanucci, J. K., & Cashdan, E. A. (2017). Sex differences in virtual navigation influenced by scale and navigation experience. *Psychonomic Bulletin & Review*, 24(2), 582-590. DOI 10.3758/s13423-016-1118-2
- Pew Research Center (2019, June). Mobile fact sheet: Mobile phone ownership over time. Pew Research Center. <https://www.pewresearch.org/internet/fact-sheet/mobile/>
- Plumert, J. M., Kearney, J. K., Cremer, J. F., & Recker, K. (2005). Distance perception in real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, 2(3), 216-233.
- Pyc, M. A., & Rawson, K. A. (2010). Why testing improves memory: Mediator effectiveness hypothesis. *Science*, 330(6002), 335-335.
- Rauhoeft, G., Leyrer, M., Thompson, W. B., Stefanucci, J. K., Klatzky, R. L., & Mohler, B. J. (2015, September). Evoking and assessing vastness in virtual environments. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception* (pp. 51-54).
- Renner, R. S., Velichkovsky, B. M., & Helmert, J. R. (2013). The perception of egocentric distances in virtual environments-a review. *ACM Computing Surveys (CSUR)*, 46(2), 1-40.
- Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & cognition*, 27(4), 741-750.
- Risko, E. F., & Gilbert, S. J. (2016). Cognitive offloading. *Trends in cognitive sciences*, 20(9), 676-688.
- Karipicke, J. D., & Roediger, H. L. (2008). The critical importance of retrieval for learning. *Science*, 319(5865), 966-968.

- Roediger III, H. L., & Karpicke, J. D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological science*, *17*(3), 249-255.
- Roediger III, H. L., & Marsh, E. J. (2005). The positive and negative consequences of multiple-choice testing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(5), 1155.
- Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic bulletin & review*, *16*(2), 225-237.
- Rowland, C. A. (2014). The effect of testing versus restudy on retention: a meta-analytic review of the testing effect. *Psychological Bulletin*, *140*(6), 1432.
- Ruddle, R. A., & Lessels, S. (2006). For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological science*, *17*(6), 460-465.
- Ruddle, R. A., Volkova, E., & Bühlhoff, H. H. (2011). Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *18*(2), 1-20.
- Ruddle, R. A., Volkova, E., Mohler, B., & Bühlhoff, H. H. (2011). The effect of landmark and body-based sensory information on route knowledge. *Memory & cognition*, *39*(4), 686-699.
- Serino, S., Morganti, F., Di Stefano, F., & Riva, G. (2015). Detecting early egocentric and allocentric impairments deficits in Alzheimer's disease: an experimental study with virtual reality. *Frontiers in aging neuroscience*, *7*, 88.
- Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive psychology*, *43*(4), 274-310.
- Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In *Advances in child development and behavior* (Vol. 10, pp. 9-55). JAI.
- Simons, D. J., & Levin, D. T. (1997). Change blindness. *Trends in cognitive sciences*, *1*(7), 261-267.
- Souman, J. L., Giordano, P. R., Schwaiger, M., Frissen, I., Thümmel, T., Ulbrich, H., ... & Ernst, M. O. (2011). CyberWalk: Enabling unconstrained omnidirectional walking through virtual environments. *ACM Transactions on Applied Perception (TAP)*, *8*(4), 25.
- Spiers, H. J., & Maguire, E. A. (2007). A navigational guidance system in the human brain. *Hippocampus*, *17*(8), 618-626.

- Squire, L. R., & Zola, S. M. (1996). Structure and function of declarative and nondeclarative memory systems. *Proceedings of the National Academy of Sciences*, 93(24), 13515-13522.
- Stankiewicz, B. J., & Kalia, A. A. (2007). Acquisition of structural versus object landmark knowledge. *Journal of Experimental Psychology: Human Perception and Performance*, 33(2), 378.
- Stanney, K. M., Kennedy, R. S., & Drexler, J. M. (1997, October). Cybersickness is not simulator sickness. In *Proceedings of the Human Factors and Ergonomics Society annual meeting* (Vol. 41, No. 2, pp. 1138-1142). Sage CA: Los Angeles, CA: SAGE Publications.
- Stokes, A. F., & Wickens, C. D. (1988). Aviation displays. In *Human factors in aviation* (pp. 387-431). Academic Press.
- Stone III, W. B. (2017). Psychometric evaluation of the Simulator Sickness Questionnaire as a measure of cybersickness. Doctoral dissertation, Iowa State University.
- Suma, E. A., Clark, S., Krum, D., Finkelstein, S., Bolas, M., & Warte, Z. (2011, March). Leveraging change blindness for redirection in virtual environments. In *2011 IEEE Virtual Reality Conference* (pp. 159-166). IEEE.
- Suma, E. A., Finkelstein, S. L. Reid, M. Ulinski, A. and Hodges, L. F. (2009). Real walking increases simulator sickness in navigationally complex virtual environments. *in Proc. IEEE Virtual Reality*, pp. 245-246.
- Templeman, J. N., Denbrook, P. S., & Sibert, L. E. (1999). Virtual locomotion: Walking in place through virtual environments. *Presence*, 8(6), 598-617.
- Tolman, E. C. (1948). Cognitive Maps in Rats and Men. *Psychological Review*, 55(4), 189-208. doi:10.1037/h0061626
- Tversky, B. (1981). Distortions in memory for maps. *Cognitive psychology*, 13(3), 407-433.
- Volz, K., Yang, E., Dudley, R., Lynch, E., Dropps, M., & Dorneich, M. C. (2016, September). An evaluation of cognitive skill degradation in information automation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 60, No. 1, pp. 191-195). Sage CA: Los Angeles, CA: SAGE Publications.
- Waller, D., & Greenauer, N. (2007). The role of body-based sensory information in the acquisition of enduring spatial representations. *Psychological research*, 71(3), 322-332.
- Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32(4), 867.

- Waller, D., Loomis, J. M., & Haun, D. B. (2004). Body-based senses enhance knowledge of directions in large-scale environments. *Psychonomic Bulletin & Review*, *11*(1), 157-163.
- Waller, D., Loomis, J. M., & Steck, S. D. (2003). Inertial cues do not enhance knowledge of environmental layout. *Psychonomic bulletin & review*, *10*(4), 987-993.
- Wang, R. F. (2016). Building a cognitive map by assembling multiple path integration systems. *Psychonomic Bulletin & Review*, *23*(3), 692-702.
- Warren, W. H., Rothman, D. B., Schnapp, B. H., & Ericson, J. D. (2017). Wormholes in virtual space: From cognitive maps to cognitive graphs. *Cognition*, *166*, 152-163.
- Weißker, T., Kunert, A., Fröhlich, B., & Kulik, A. (2018, March). Spatial updating and simulator sickness during steering and jumping in immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 97-104). IEEE.
- Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(3), 669.
- Wolbers, T., & Büchel, C. (2005). Dissociable retrosplenial and hippocampal contributions to successful formation of survey representations. *Journal of Neuroscience*, *25*(13), 3333-3340.
- Maguire, E. A., Woollett, K., & Spiers, H. J. (2006). London taxi drivers and bus drivers: a structural MRI and neuropsychological analysis. *Hippocampus*, *16*(12), 1091-1101.
- Zhang, H., Copara, M., & Ekstrom, A. D. (2012). Differential recruitment of brain networks following route and cartographic map learning of spatial environments. *PloS one*, *7*(9).

APPENDIX

IRB APPROVAL MEMO

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 08/20/2019

To: Alex F Lim Jonathan W Kelly

From: Office for Responsible Research

Title: **Memory and virtual environments**

IRB ID: 19-374

Submission Type: Initial Submission **Review Type:** Expedited

Approval Date: 08/20/2019 **Approval Expiration Date:** N/A

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- Use only the approved study materials in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.
- [Retain signed informed consent documents](#) for 3 years after the close of the study, when documented consent is required.
- Obtain IRB approval prior to implementing any changes to the study or study materials.
- Promptly inform the IRB of any addition of or change in federal funding for this study. Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an [eligible PI](#) to remain open.
- Immediately inform the IRB of (1) all serious and/or unexpected [adverse experiences](#) involving risks to subjects or others; and (2) any other [unanticipated problems](#) involving risks to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

IRB 01/2019

those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to [post-approval monitoring](#) by Iowa State University's Office for **Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.
- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the [IRB Study Closure Policy](#).

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.
- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 7/14/2017

To: Alex F Lim
1620 Lagomarcino

CC: Dr. Jonathan W Kelly
W112 Lagomarcino

From: Office for Responsible Research

Title: Navigating with GPS in a driving simulator

IRB ID: 17-258

Approval Date: 7/14/2017

Date for Continuing Review: 7/13/2019

Submission Type: New

Review Type: Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.
- **Retain signed informed consent documents for 3 years after the close of the study**, when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.
- **Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- **Stop all research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.
- **Complete a new continuing review form** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.