COMPARING THE DOMINANT AND CONTINUOUS THEORETICAL FRAMEWORKS OF SPATIAL MICROGENESIS

by

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B.F.A., Emporia State University, 2005
M.A., Kansas State University, 2007

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
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Abstract

The theoretical framework of spatial microgenesis as presented by Siegel and White (1975), and updated by Montello (1998) posits that through exposure, humans will create spatial knowledge of places in their minds. This process is thought to be an ongoing one, and will eventually lead to a metrically-scaled 'map-like' image in the mind. In Siegel and White's dominant framework, knowledge of space progresses through the stages of landmark and route, and ends with survey knowledge, whereas in Montello's continuous framework, metrically-scaled survey knowledge is present from the first exposure. Beyond that primary difference between the two theoretical frameworks, the continuous framework also provides for greater nuance in how the process may occur for different individuals.

There is little research directly addressing the differences between the two frameworks, and this dissertation adds support for the continuous framework by testing three of its five tenets. Utilizing a virtual environment as a laboratory, participants were exposed to a novel environment and asked to complete spatial tasks based on knowledge of the layout of said environment. Over the course of three sessions, measures of spatial knowledge were recorded using distance, direction, and sketch map tasks.

The results support the first tenet of the continuous framework: metrically-scaled survey-type knowledge was found in all participants beginning with the first session. The concepts of landmark, route, and survey knowledge are still valuable though, as the results clearly showed that they help to describe the way that individuals conceptualize mental representations of space. These conceptualizations may potentially be valuable as a component of a larger spatial ontology for the American public school system. Regarding tenet two, some improvement in error rates was observed over time, but not at a statistically significant rate for all tasks, suggesting that other factors such as the study length and motivating factors may have played a role in performance. Tenet four was also supported, with significant variation in performance between participants with similar levels of exposure to the environment. Overall, this dissertation finds that the continuous framework is largely correct in its descriptions of the process of spatial microgenesis, albeit with some elements that are not fully supported by the data collected. Despite not being a good model of the process, the dominant framework remains valuable for describing how people conceptualize their spatial knowledge of environments.

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Dedication

I would like to dedicate this dissertation to my wonderful wife Amy and our two cats. All three of them put up with a lot while I went through this process.

Chapter 1 - Introduction

As humans, we make use of spatial skills every day. Whether it is traveling to work or attempting to find a friend's house, our ability to function in the world relies on our ability to understand the spatial organization of places and navigate using that knowledge. While we now have a dizzying array of technologies to help us with this task, ranging from traditional paper maps to any number of high-tech GPS-embedded devices, we all must rely to some degree on our internal mental abilities. Imagine for a moment that you have just moved to a new city and are learning your way around. Yes, you may be forced to rely on your GPS-enabled smartphone for the first few days, but over time you gain a better understanding of the layout of your new neighborhood. Or perhaps you've started a new job in a building that you've never previously entered. During your first week, it may be a struggle to remember where the copy room is, but over time you have no trouble finding different offices. These are experiences that virtually all of us have encountered at one point in our lives. It may happen consciously or subconsciously, but we all create cognitive maps of the spatial layout of places. These maps serve our navigational needs by answering four important questions: "….whether to go somewhere; why go there; where [the destination is]; and how to get there" (Kitchin 1994, pg. 7). These vital questions apply whether we are talking about navigation within a building, across town, or across the globe.

The process that describes how people acquire knowledge about the spatial layout of the world around them is called spatial microgenesis (Montello 1998). Spatial microgenesis has also been referred to as 'cognitive mapping' by Downs and Stea (1973), who used a similar definition of the process: "Cognitive mapping is a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment" (pg. 9). Other researchers have also discussed this process and what it entails, such as the influential views of Siegel and White (1975). They explain it as a progression through three states of spatial knowledge: landmark, route, and survey knowledge. In this framework, landmarks are objects that stand out from the surrounding area and are remembered as 'snapshots' or images. Using landmarks, route knowledge is then generated as a series of pathways from one landmark to the next in a linear fashion. As many routes grow and overlap, they reach the final stage of survey knowledge, which is an allocentric, metrically-scaled, map-like mental representation of space. This survey state is a sophisticated understanding of space in which individuals can create and navigate through novel pathways based on the completeness of their knowledge of the space.

Siegel and White's theoretical framework has been an important influence on the thinking about the subject for many years, and has come to be referred to as the *dominant framework of spatial microgenesis*. More recent work by Montello (1998) expands and clarifies the dominant framework with what is referred to as the *continuous framework.* Broadly speaking, the continuous framework describes spatial microgenesis as a process in which people continuously gather and integrate metrically-scaled spatial information about the environments they inhabit. One of the largest differences between Montello's work and the dominant framework is that the continuous nature of Montello's framework shows that people gain metrically-scaled survey knowledge from the first exposure to place, circumventing the three step process described by the dominant framework. Another important element of the continuous framework is that it states that given the same level of exposure to a place, different individuals will have different amounts of knowledge. Large differences in individual ability have been found in prior work, and this has made it difficult to make general statements about the process of spatial microgenesis.

While the continuous framework is certainly well constructed and supported by many observations and citations of spatial ability, there is a paucity of research that directly addresses the differences between it and the dominant framework. Ishikawa and Montello (2006) test some of the tenets of the continuous framework and find that while most of them appear to be correct in describing the process of gaining spatial knowledge, there are some issues, most notably the fact that there were no consistent signs of improvement of knowledge across participants. Schinazi *et al.* (2009) also conducted a similar experiment to the one done by Ishikawa and Montello and found similar results. Beyond these studies, there is little research that directly looks at the contributions to the understanding of spatial microgenesis provided by the continuous framework.

This dissertation aims to add to the understanding of the two frameworks by providing more independent data on the topic. The primary question this research seeks to answer is whether or not the continuous framework does a better job of explaining spatial microgenesis than the dominant framework. If the dominant framework is correct, spatial knowledge should progress over time through the three distinct stages it describes. If the continuous framework is correct, gaining spatial knowledge should be better described by the five tenets. This dissertation will test the three most relevant of the five tenets of the continuous framework to see if they correctly predict behavior.

The first tenet states that there is no stage of pure landmark or route knowledge, but rather that metrically-scaled survey-type knowledge exists from an initial exposure. For testing this tenet, the hypothesis is that no pure landmark or route knowledge will exist after an initial exposure to a novel environment; the null hypothesis being that evidence of landmark and route knowledge as described by the dominant framework will exist. The second tenet says that spatial knowledge will grow over time. The hypothesis for this tenet is that error in spatial tasks will significantly decrease after repeated exposures to an environment; conversely, the null hypothesis is that no statistically significant evidence of improvement will be found. Finally, the fourth tenet posits that given similar levels of exposure to place, individuals will have different levels of spatial knowledge. The hypothesis related to this tenet is that all groupings of individuals with similar exposure will show variation in their performance on spatial tasks. The null hypothesis in this case is that no variation will be found within groupings of individuals' performance on spatial tasks. It is worth noting that what constitutes a high level of variance is dependent on the subject being studied. For example, a factory mass-producing a product will demand extremely low levels of variance, as opposed to an academic setting where it is understood that higher levels of variance will exist in student performance. This research aims to provide a baseline for showing what typical levels of variance are in regard to spatial abilities among groups of individuals.

In order to test these hypotheses it was necessary to measure individuals' ability to learn the layout of a novel environment over time. This raised some logistical issues, the first being the need for a novel environment to use at an appropriate spatial scale; the second getting a suitable pool of participants who could commit to attending multiple research sessions over an extended period of time. Spatial microgenesis is not a 'one-shot' activity. As both the dominant and continuous frameworks state, it is an ongoing process, and studying it required participants to attend multiple sessions in order to measure the progression of spatial knowledge. Research participants were recruited from geography courses at Kansas State University (KSU) and compensated in extra credit, the details of which are described in the methods chapter of this dissertation.

Spatial microgenesis is concerned with the acquisition of spatial knowledge in large-scale environments, so a space larger than a table top or single room would be required. The city of Manhattan, Kansas where the main KSU campus is located is not particularly large in terms of area, and it would be somewhat unlikely that a particular neighborhood would be completely unknown to the student population. Additionally, it would be costly, time consuming, and a potential safety risk to transport a large number of participants to a real-world environment for exploration. Schinazi *et al.* (2010) discusses some of these issues, namely that in Schinazi *et al.* (2009), the amount of time required for data collection in the real world was quite large. Beyond an initial round of real-world data collection, their conclusion was the same as the one reached in this research: use of a virtual environment reduces the time and effort necessary for data collection. Virtual environments can offer many benefits when it comes to conducting this type of research such as low costs, flexibility, and a high degree of researcher control over the environment. For example, when using a virtual environment there is never any concern about unwanted changes occurring in the spatial layout such as road construction, or rainy days getting in the way of data collection. In the case of this research, a desktop virtual environment was employed, meaning that it used standard computer LCD monitors to display the environment. This helped to keep the cost low, as expensive virtual reality goggles and other exotic computing hardware were not required. Most research institutions already have computer labs that are capable of running desktop virtual environments, and KSU's geography department is no different. Realistic 3D virtual environments cannot be run on all computers (laptops in particular tend to have insufficient graphics capabilities), but the vast majority of modern computer hardware is capable of running the software employed in this research.

However, the virtual approach is not without weaknesses. Compared to the real world, virtual environments impart a lower amount of spatial knowledge to those who experience them. Even in immersive, head-mounted virtual reality setups, participants never truly experience the proprioceptive component of spatial knowledge, meaning that the body does not gain any physical motion cues. Likewise, most virtual environments feature a narrow field of view (meaning peripheral vision is limited, the virtual environment used in this study has a field of view of 75°) when compared to real life conditions, which are typically around 160° (Aber, Marzolff, and Ries 2010). In general, within desktop virtual environments peoples' ability to gain spatial information is reduced when compared to their performance in the real world (Montello, Hegarty, Richardson 2004, Richardson, Montello, and Hegarty 1999). However, reduction does not imply nonexistence. Desktop virtual environments are suitable for this type of research and have been used to study phenomena related to spatial abilities in humans in a variety of studies (see Cubukcu and Nasar 2005; Wan, Wang & Crowell 2009; and Williams *et al*. 2007 for a few examples).

For this research a visually-rich desktop environment was desired, and commercial video games turned out to be a useful, if unexpected fit. The financial success of a commercial video game in the market relies in large part on drawing players into a virtual world that they enjoy. One way they do this is by striving for a strong sense of presence, or immersion, in the virtual environment. Due to the restrictions of two dimensional televisions and computer monitors, a great deal of effort is expended by game developers through the use of audio and visual stimuli to help create a sensation of physical presence in the game world; see the game *Mirror's Edge* (2008) for perhaps the best example of this. Because of this effort, game technology is responsible for some of the most immersive experiences that can be found in desktop virtual environments. Games on consoles such as the Sony PlayStation 3 or the Microsoft Xbox 360 certainly benefit from this development effort, but cannot easily be adapted for research purposes as the software tends to be 'closed' to the end user. As a contrast to consoles, games on computers often come with editors that allow players to modify and create their own virtual environments, which was a perfect fit for the needs of this research.

The game chosen to facilitate the virtual environment for this study was *Left 4 Dead* (**Figure 1.1**), a first-person shooter made by Valve Software (*Left 4 Dead* 2008). It meets the needs of the research in that it can be modified, it employs a first-person perspective, and it has a high level of visual and auditory fidelity. The game comes with a suite of editing tools for creating and modifying content, in particular the *Hammer World Editor*, which allows for the modification of the game environment's geometry. The editor is powerful and complex (it is the same suite of tools that were used by Valve to originally create the game), and following the provided tutorials is recommended. Once the basics of how to use the editor were learned, modifying the game environments to be used for research purposes is a straightforward process.

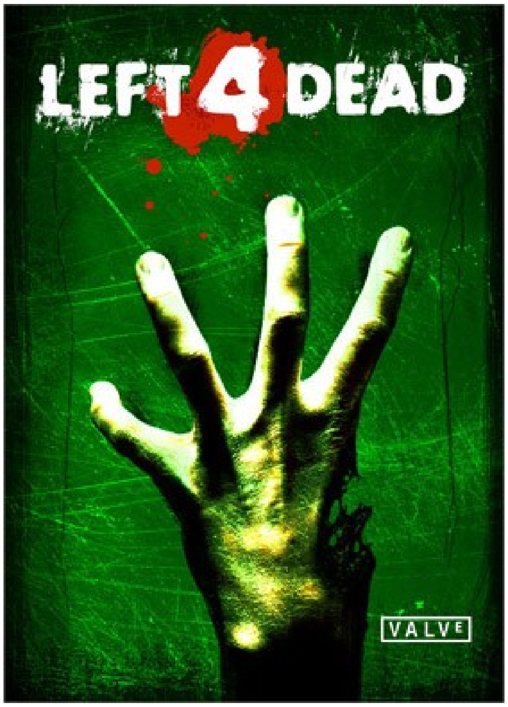


Figure 1.1 – Cover art for the game *Left 4 Dead,* which provided the virtual environment used in this research.

Figure 1.2 – An image of the game world of *Left 4 Dead*. This image shows the environment before it was modified for use in this research.

The first person perspective provided by *Left 4 Dead* is important, because of all the various perspectives employed in virtual environments, it most closely mimics human vision. Essentially the image on the screen is seen as if the monitor were the player’s eyes. By moving the player’s view toward the ground, the player’s feet are visible, and their hands are seen at the bottom of the screen holding various items that allow for interaction in the virtual world. This kind of perspective, when combined with visual and auditory cues (*e.g.*, the view bobs during motion, the player’s body, or avatar, casts a shadow, and motion creates the sound of footfalls) creates a realistic, immersive experience of the virtual environment (an image from the game world can be seen in **Figure 1.2**). The high level of visual fidelity is an important element; some research has relied on technology that provides a low resolution, unrealistic environment. This is understandable, since providing stereoscopic virtual reality goggles with a realistic image is computationally expensive. Since commercial video games are at the forefront of graphical realism in virtual environments, this helps to bring the real and virtual worlds closer without requiring cost-prohibitive amounts of computing hardware. While it would be a stretch to say that the environments in *Left 4 Dead* are a one-to-one experience when compared to reality, it definitely comes closer to a real-world experience when compared to some of the virtual environments used in prior research settings. This level of quality in the visuals helps to create an immersive sense of presence, or a sense of ‘being there’.

The following chapters will explain some of the historical thinking on the subject of spatial microgenesis, as well as other topics related to the subject; describe the methods employed in the research; and discuss the results of the data collection. At various points in this text, readers may be referred to one of the appendices which contain additional information related to the research, which can be found following the citations chapter at the end of the dissertation.

Chapter 2 - Literature Review

Spatial Thinking

Before discussing spatial microgenesis directly, it is important to understand how it fits into the broader context of spatial thinking. Spatial thinking is a blanket term that encompasses many aspects of spatiality, and is described by the National Research Council's "Learning to Think Spatially" as follows:

> "Spatial thinking uses representations to help us remember, understand, reason, and communicate about the properties of and relationships between objects represented *in* space, whether or not those objects themselves are inherently spatial." [Emphasis preserved] (National Research Council 2006, pg. 27)

This could include such disparate activities as navigating a city, working with an internal combustion motor, exploring the structure of chemical compounds, or the interpretation of data visualizations such as graphs; skills used in many professions that are not typically thought of as spatial in nature. Spatial thinking can be defined more succinctly as a "constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning" (National Research Council 2006, pg. 12). This dissertation is primarily concerned with the representation functions of spatial thought, particularly the concept of cognitive maps. Without cognitive maps and the processes that help create them, we would be limited in our ability to engage in the spatial reasoning crucial to the STEM fields (Science, Technology, Engineering, and Math), not to mention the difficulty we would experience in a simple trip to the grocery store! The process that creates those cognitive maps, spatial microgenesis, is the primary focus of this research. Spatial microgenesis is in turn made possible by some of our most basic spatial abilities and mental processes known collectively as spatial updating. The literature review will begin with the most basic components, our spatial updating abilities, and work out, ending with larger concepts of how spatial thinking relates to the discipline of geography and spatial education.

Spatial Updating

In understanding spatial microgenesis, it is useful to have some knowledge of how the brain processes and uses spatial information. The term 'spatial updating' refers to the mechanisms which allow us to learn about space, and as such, is important to the process of spatial microgenesis (Klatzky *et al.* 1998). Without the mechanisms involved in spatial updating, we would be unable to locate ourselves within an environment, gain knowledge about the space around us, or navigate through that space. In the past, it has been suggested that the process of spatial updating was like viewing a map, with an allocentric, external frame of reference (Behrmann and Tipper 1999; O'Keefe and Burgess 1996). In this context, allocentric refers to the fact that everything we know spatially is tied to an external reference larger than ourselves, such as map coordinates (Wang *et al.* 2006). Today, some research suggests that spatial updating is an egocentric process, meaning that interpretations of space are relative to ourselves (Wang and Spelke 2000; Wang *et al.* 2006). Rather than viewing objects as being elements at specific coordinates on an internal reference system, we think of objects' locations in relation to ourselves and in relation to other objects. A visual example of the difference between allocentric and egocentric perspectives can be seen in **Figure 2.1**.

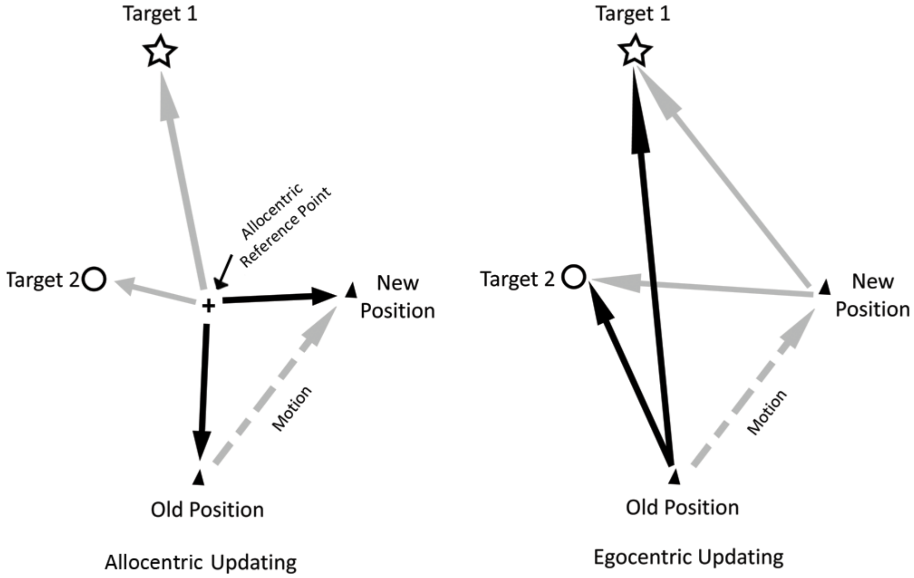


Figure 2.1 – A visual example of the difference between allocentric updating and egocentric updating (adapted from Wang *et al.* 2006).

Understanding space is achieved by three different processes that work together in the human mind: path integration, place recognition, and reorientation. These three processes have also been observed and studied in animal species, which has helped to give us insight to how they work in the human mind (Wang and Spelke 2002). For example, the honeybee has been shown to make use of both path integration and place recognition to find their way back to the hive (Collett and Collett 2000).

Path integration is the process of updating the location of significant objects relative to an individual (Etienne and Jeffery 2004). This is achieved by representing object locations as vectors relative to the individual. As a person moves, the vector of motion is continuously and automatically subtracted from the vector of the object in order to update the location relative to the person. This skill is common to humans, and has been shown to operate even among those who are congenitally blind, a group who cannot take advantage of the other two spatial updating abilities described here as they rely on vision (Loomis *et al.* 1993).

View-dependent place recognition is the second mechanism by which we are able to update our location (Wang and Spelke 2002). These are views of objects from specific positions that are remembered and are used as landmarks during navigation. Because they are view-dependent, the further one deviates from the view of the landmark as it is stored in memory, the more difficult it becomes to recognize the object as the landmark.

The third mechanism of updating is reorientation. Reorientation operates by allowing people to understand the shape of places they are in (Hermer and Spelke 1996). The geometric properties of places (*e.g.* rooms, fields, mountains, etc.) allow individuals to reorient themselves when other types of navigation are disrupted. For example, if no landmarks are visible, and enough time has passed that path integration is not possible, the shape of an area could be used to help an individual with successful navigation. The combination of these three techniques for monitoring and learning about our spatial environment allows us to navigate.

The egocentric nature of spatial updating explains why humans have trouble understanding relationships between separately learned places. For example, we may be familiar with the layout of a university campus, and we may also be knowledgeable about the layout of a particular building on that campus, but once inside the building, we have trouble understanding where the other buildings on campus are in relation to our position (Wang and Brockmole 2003). This is in part because when we enter the building, we have lost our outdoor landmarks such as iconic buildings and the position of the sun and cannot rely on them to assist us with orientation. We cannot see where things ‘should be’ in relation to these landmarks because they are no longer in view. Inside the building, it takes us longer to orient outside elements because we must first think of our position relative to a landmark on the building (say, the front entrance), then orient that landmark in relation to the rest of the campus. It also explains why understanding layouts from one floor to the next can be difficult, as the movement and potential rotation involved when walking up a flight of stairs causes us to lose our orientation.

Despite this view that spatial updating is an egocentric process, some research has suggested that it may actually be a dual-system process (Mou *et al.* 2004). In this model, working memory is guided by an egocentric approach, but long-term memory is thought to be allocentric in nature. As Gersmehl and Gersmehl (2006, 2007) discuss, it may also be possible that humans switch between multiple frames of reference, egocentric and allocentric, depending on the spatial context. They point to a body of psychological literature that backs this up, including Nardini *et al.* (2006), who show that even young children who have in the past been presumed to be less advanced in their ability to think spatially (see Piaget and Inhelder 1967; Hart and Moore 1973), are able to take advantage of multiple frames of spatial reference, egocentric and allocentric. The idea of a dual-system process with egocentric updating and allocentric long-term memory fits well with the theoretical frameworks of spatial microgenesis that are discussed in the next section of this literature review. While not all of them comment directly on the frames of reference employed by the brain, they all posit that the end product is an allocentric representation of space.

Spatial Microgenesis

As previously discussed, spatial microgenesis is a developmental process that describes how people acquire knowledge about the spatial layout of the world around them. Simply put, spatial microgenesis says that we will learn about a novel environment as we experience it, and the more time we spend exploring it, the more we will learn (Montello 1998). It is unlikely that this learning process ever ends, even after decades, but our knowledge of the space will continue to become more accurate as time goes on. The product of this process is a cognitive map, such as those Tolman described in his famous ‘Cognitive Maps in Rats and Men’ (1948), albeit a map that is continually updated throughout one’s life. Of course this understanding of spatial microgenesis did not appear fully formed; it has been refined over many decades of thought.

Originally published in 1948, Piaget and Inhelder’s ‘The Child’s Conception of Space’ (1967) discussed the concepts relating to spatial microgenesis in different terms: topological, projective, and Euclidean. Topological space is concerned with qualitative relationships such as proximity, separation and continuity. Projective space deals with spatial relations fixed to specific viewpoints in an egocentric frame of reference. And Euclidean space describes metrically-scaled information about distances and directions. They argued that in children a progression through these stages of knowledge existed, that topological space was understood earlier and more complex projective and Euclidean knowledge developed at a later time date. This view was later challenged, with evidence showing that even young children can use the more 'advanced' stages at an early age (Nardini *et al.* 2006).

Hart and Moore (1973) expanded on the ideas of Piaget and Inhelder and described space through three frames of reference: egocentric, fixed and coordinated. Through a review of prior literature, they also posited that spatial knowledge developed in children from a more limited egocentric perspective to a more complex allocentric view as they grow from childhood to adolescence. This idea is repeated in suggestions that our spatial updating abilities may rely on an egocentric view for working memory, and an allocentric representation for long-term memory (Mou *et al.* 2004), although as mentioned above, more recent research suggests that Hart and Moore are incorrect (Nardini *et al.* 2006).

Siegel and White (1975) are responsible for what is considered the dominant theoretical framework for understanding spatial microgenesis. Building upon the research described above, they created a framework in which learning begins with landmark knowledge, moves to route knowledge, and finally ends in a state of survey knowledge. Landmarks are objects that stand out from the surrounding area and are remembered as 'snapshots' or images. This stage of knowledge is related to the spatial updating process of place recognition, and draws from Piaget and Inhelder's (1967) description of projective knowledge. Following landmark knowledge, route knowledge is generated. This is a series of pathways from one landmark to the next in a linear fashion. This allows for navigation, but does not imply a true metric understanding of the environment. The final stage of spatial learning is survey knowledge, which is an allocentric, metrically-scaled, map-like representation of space. Survey knowledge is considered a significant leap in the understanding of space, and generally only occurs after a great deal of exposure to a place. The idea of route and survey knowledge also comes from Shemyakin's 1961 piece, *Orientation in Space*. He argued that route knowledge is created prior to the creation of survey-type knowledge, and that survey knowledge was only possible through the integration of large amounts of route knowledge.

In 1978, Golledge and Spector put forth a theoretical framework known as the Anchor-Point Theory. It does not focus specifically on the progression or growth of knowledge; instead it attempts to describe the structure of cognitive maps. This framework shares common elements with the dominant framework from Siegel and White, where primary nodes or anchors (landmarks) are important as key primitive elements of the environment. Anchor points are then connected by paths (routes), and area is added to that point-line information to describe “a more general spatial property of the major components of a spatial representation of phenomena” (pg. 406). Although anchors and landmarks have been equated here, it is important to note that the Anchor-Point Theory distinguishes between the two (Couclelis *et al.* 1987). Landmarks as popularized by Lynch (1960) are objects or locations that stand out from the environment at a collective level, whereas anchors may be much more personal and individual as opposed to collective in their recognition. For example, a church may be a landmark in a community due to its unique architecture and social role within that community, while an otherwise nondescript office building in the same community may be an extremely important landmark to an individual who works there while remaining invisible to others. Landmarks in the dominant framework are more closely associated with the personal anchors of the Anchor-Point Theory than the landmarks described by Lynch.

Anchor-Point Theory recognizes that four types of knowledge are implicit in cognitive maps: ‘knowing-what’, ‘knowing-how’, ‘knowing-where (absolute)’, and ‘knowing-where (relational)’ (Couclelis *et al.* 1987). The ‘what’ component covers objects in the environment and the ‘how’ component deals with the knowledge necessary for navigation (whether that navigation is mental or actual). The two ‘where’ components deal with the location of objects, the ‘absolute’ knowledge dealing with metric Euclidian space and the ‘relational’ knowledge dealing with issues of subjective locations. Much like other research before it, the Anchor-Point Theory describes a dual-encoding system for spatial knowledge, where a continuum exists from purely egocentric knowledge of the world to more allocentric cognitive structures that are constructed over time. However, the theory recognizes that while later-stage knowledge of space will be more allocentric in nature, the representations of space will remain distorted and fragmentary to some degree (Golledge and Spector 1978, pg. 409).

Research has found that Siegel and White’s dominant theory does not hold up well when real world conditions are examined. For example, Gärling, Böök, and Ergezen (1982) found that spatial knowledge did not progress through the three stages proposed by Siegel and White, but rather that relative locations of objects were learned before routes. That alone would be problematic enough for the dominant theoretical framework, but a much bigger critique comes from Montello (1998), who proposed an updated continuous framework to provide a more accurate description of the process. The biggest change in the continuous framework is the observation that people have some amount of metric knowledge (knowledge implying a survey level of understanding) of a place from the first exposure to a novel environment, counter to the order that Siegel and White proposed. The five tenets of the continuous framework are:

1) There is no stage of pure landmark or route knowledge as described by Siegel and White, metric knowledge exists to some degree from the first exposure to a novel place;
2) As experience grows with a place, so too does spatial knowledge;
3) The integration of separately learned places into a hierarchically-organized knowledge structure is a sophisticated step in the microgenesis of spatial knowledge;
4) Individuals with similar amounts of exposure to a place will differ in the extent and accuracy of their spatial knowledge; and
5) Linguistic systems provide for the existence of relatively pure topological knowledge. Such non-metric knowledge exists in addition to metric spatial knowledge, not as a necessary precursor or intrinsic part of it (Montello 1998).

While Montello's continuous framework does not dismiss Siegel and White's work entirely, it does suggest that many of the details of the process were overly simplified. The new framework is an improvement, but not beyond criticism. Ishikawa and Montello (2006) found in a longitudinal study that while some individuals had an incredible level of skill at learning and recalling space accurately, others showed little to no improvement in their understanding of the space used in the study. The lack of improvement is problematic to the continuous theoretical framework, especially in the context of the second tenet, as it suggests that even with an active engagement in the process of collecting spatial knowledge some people may have difficulty learning regardless of the amount of exposure. Also, while the continuous framework does makes room for individual differences, the question of why some excel at learning and others are extremely poor at the same task remains unanswered. At this point the framework remains more of a description of what may happen rather than an explanation of how people gather and compile spatial knowledge. As Ishikawa and Montello (2006) point out, the continuous framework is a good description of how people with a good sense of direction operate, rather than an all-encompassing theory. More understanding of how the individual components of the framework behave is needed.

Spatial Microgenesis and the Experience of Space

The process of spatial microgenesis produces different results depending on how space is experienced (Montello, Hegarty, and Richardson 2004). Experiencing a place on foot will differ from experiencing it in a moving vehicle, watching it on a video monitor, or navigating through a virtual environment. Part of this difference in spatial knowledge comes from the lack of proprioceptive information in situations involving simulated motion through space (Klatzky *et al.* 1998). Another component is that by experiencing a place through a video or virtual interface, one loses much of their peripheral vision, which limits the amount of spatial information that is gained at any one time. Video games are specifically mentioned as a subset of virtual worlds that are an avenue for future research by Montello, Hegarty, and Richardson (2004). Games are highly mediated virtual environments and the process of spatial microgenesis may have different outcomes in these environments: “Similarly, we can also ask how the increasing use of video games and more sophisticated virtual environments will change the way people think about and remember space and place” (p. 279). It is possible that video games encourage certain types of thinking related to gathering spatial knowledge that is not normally experienced in typical day-to-day navigation of space.

In the context of this research, virtual environments are important, since one originally created for a commercial video game was utilized for data collection purposes. That being said, the virtual environment used is not truly a game, as it was considerably modified through the removal of crucial gameplay elements. This ensured that a high-quality virtual environment was available for exploration without the distraction of the game component. This follows the lead of many studies that have used virtual environments to observe and test spatial abilities (Cubukcu and Nasar 2005; Richardson, Montello, and Hegarty 1999; Wan, Wang & Crowell 2009; Williams *et al.* 2007; and Witmer, Sadowski, and Finkelstein 2002). In one particular study by Hegarty *et al.* (2006), a virtual environment was created and used for research on individual differences in spatial abilities based on the commercial PC video game *Duke Nukem 3D*, showing a precedent for using commercial games as research tools. In addition, studies such as Jansen-Osmann, Schmid and Heil (2007) and Schinazi *et al.*, (2010) used commercially available

3D game engines, that is, the software frameworks for creating games (*3D GameStudio A5* and *Unity 3D*, respectively) to create their test environments. Anecdotal evidence for the creation of survey-type knowledge from video game virtual environments exists as well. In the context of literacy education, Ranker (2006) gives a case study of a student who described and drew highly detailed survey style maps of the virtual environments within the game *Gauntlet Legends* (Midway Entertainment 1999). Obviously the virtual spaces in video games are quite different from real world environments, but the studies mentioned show that not only can spatial knowledge be gained from these environments, but that the environments can be successfully used to measure spatial abilities as well.

Geographic Connections

As a spatial field of study, geography is heavily involved in the production, interpretation, and analysis of maps of all kinds. The field of geography has historically been concerned primarily with cataloging and representing objects spatially (Golledge 2002). In fact, geography's relationship to maps was once described by Hartshorne (1939) as: "So important, indeed, is the use of maps in geographic work, that, ... if (the) problem cannot be studied fundamentally by maps – usually by a comparison of several maps – then it is questionable whether or not it is within the field of geography" (pg. 249). Maps remain an important part of geography today, but in recent decades geography has grown to understand the importance of not only knowing where things are, but why and how they are. The approach to problem solving provided by modern 'geospatial' thinking is something that is valuable and unique to geography as a field (Goodchild 2001; Hegarty *et al.* 2002). Reginald Golledge's 2001 presidential address to the Association of American Geographers (2002) addressed this shift in the way geographers approach problems by describing a list of geographic thinking and reasoning processes culled from literature on spatial thought. This is a subject that Golledge had worked on for many years at that point, starting with his identification of four 'spatial primitives', location, identity, magnitude, and space-time, from which all other spatial concepts can be built (Golledge 1990, 1992, 1995).

Tier	**Geospatial Concept**	**Grade**												
		K	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Primitive	Spatial Primitives	X	X	X	X	X	X	X	X	X	X	X	X	X
Simple	Relative Distance/Direction	X	X	X	X	X	X	X	X	X	X	X	X	X
	Shape		X	X	X	X	X	X	X	X	X	X	X	X
	Place-based Symbol		X	X	X	X	X	X	X	X	X	X	X	X
Difficult	Boundary			X	X	X	X	X	X	X	X	X	X	X
	Connection			X	X	X	X	X	X	X	X	X	X	X
	Distribution				X	X	X	X	X	X	X	X	X	X
	Pattern				X	X	X	X	X	X	X	X	X	X
	Reference Frame				X	X	X	X	X	X	X	X	X	X
	Coordinate/Grid				X	X	X	X	X	X	X	X	X	X
	Zone					X	X	X	X	X	X	X	X	X
Complicated	Map						X	X	X	X	X	X	X	X
	Legend						X	X	X	X	X	X	X	X
	Map Projection						X	X	X	X	X	X	X	X
	Slope/Gradient							X	X	X	X	X	X	X
	Scale							X	X	X	X	X	X	X
	Surface								X	X	X	X	X	X
	Hierarchy										X	X	X	X
	Overlay										X	X	X	X
Complex	Interpolation											X	X	X
	Global Climate Change												X	X
	Spatial Association												X	X

Table 2.1 – Sample Educational Spatial Task Ontology. Adapted from Golledge, Marsh and Battersby 2007.

In later work these four spatial primitives (and the increasingly complex concepts they can build) were refined into a spatial task ontology, which is an "explicit specification of a conceptualization" (Gruber 1993). This ontology was designed with the American public education system in mind (Golledge, Marsh, and Battersby 2007; 2008; Marsh, Golledge, and Battersby 2007). Looking at a potential example of this spatial task ontology in **Table 2.1** (adapted from Golledge, Marsh, and Battersby 2007), one can see how more complex tasks build from lesser ones, inheriting elements of the less complex concepts. The creation of this kind of spatial task ontology is important, as spatial education is an area of instruction that is sorely lacking from the American public school curriculum (Golledge 2002). As has been mentioned previously, spatial tasks surround us. Virtually all activities and fields of study involve spatial considerations of one sort or another (Golledge, Marsh, and Battersby 2007). Many activities are explicitly spatial, like team sports, delivering packages, or driving a taxi, but many activities in our daily lives are explicitly spatial while having little or nothing to do with navigation or physical motion. Tasks such as interpreting and understanding graphs, dealing with the organizational structure of a company, and interpreting MRI scans are not necessarily thought of as spatial, but rely on spatial thinking skills. In regards to education, older views suggested that young children did not have the capacity to understand more complex spatial ideas, but Gersmehl and Gersmehl (2006, 2007) have done a review of literature that shows eight distinct spatial concepts (some of which may be 'hardwired' into the human mind), and that children as young as three years old could understand these eight spatial concepts to some degree. These skills also appear to be at least somewhat cumulative, meaning that those who develop the skills in early childhood will be able to build upon them as they grow older and gain more knowledge (Gregg 1999; Uttal 2000).

This is valuable beyond our day-to-day activities as spatial skills have strong links to the sciences, or as the National Research Council (2006) strongly worded it: "Spatial thinking is deeply implicated in the conduct of science" (pg. 55). All fields of science rely on spatial thinking, but explicitly spatial fields, like GIScience, have a need for more spatial thinkers in order to address some of the bigger GIScience challenges, such as those identified by Goodchild (1992, 2010). One factor that hinders the development of spatial thinkers is an underperforming public educational system in America. In the Organization for Economic Co-operation and Development's 2009 *Program for International Student Assessment*, America ranked 32nd in mathematics and 23rd in science among developed nations (OECD 2010). Given this lagging performance in STEM education, showing that early intervention in spatial education can help build to later success in spatial thinking is a valuable finding. An improved effort to teach spatial thinking in public schools could have broad-reaching effects, with individuals having greater capacity to deal with spatial tasks as adults both in the sciences and everyday life.

Gersmehl and Gersmehl's review of educational literature draws heavily from the field of psychology, as psychologists have insights to human spatial abilities that geographers could not uncover on their own (Gersmehl and Gersmehl 2006, 2007). The eight spatial concepts identified by Gersmehl and Gersmehl include comparison, aura (or zone of influence), region, hierarchy, transition, analogy, pattern, and association. Clearly this list covers much of the same territory as Golledge, Marsh, and Battersby's (2007) spatial task ontology, and in many ways they complement each other. For example, Golledge's spatial task ontology has the concept of pattern listed as a difficult concept that could be taught in grade three (see **Table 2.1**). Research by Tada and Stiles (1996) indicates that children as young as three years old can recognize patterns, but cannot recreate them on paper until the age of six or seven. Given this age range, teaching students about geographic patterns in grade three (approximate age of nine years old) would be appropriate. Additionally, while research indicates that children understand the concept of hierarchy at early ages, they become easily overloaded with uncategorized information (Sandberg 1999). In light of that, the spatial ontology's placement of hierarchy at the ninth grade level would be appropriate. Obviously, as more knowledge is gained about the development of spatial skills in children these lists can be refined, particularly in regards to the most appropriate ages for concepts to be included in the curriculum and the best ways to introduce and teach the concepts.

While understanding recent research in geographic education may seem a bit removed from spatial microgenesis, the two topics are not as distant as they might appear. As the discussion above covers, exposure to an ordered sequence of geographic/spatial concepts at young ages can lead to improvements in general spatial thinking that may affect the process of spatial microgenesis. Educational backgrounds may also play a role in the individual differences in spatial ability found from one person to another. Ishikawa and Montello (2006) found a wide disparity in ability between individuals, and education may be a factor in explaining some of those differences. Geographers understand the necessity for education on spatial topics, as evidenced by calls for greater spatial curricula from authors like Solem, Cheung, and Schlemper (2008) and the National Research Council's *Beyond Mapping* and *Learning to Think Spatially* (both 2006), but it can often be a hard sell to those who are unaware of the importance of thinking spatially. *Beyond Mapping* argues that more GIS instruction should be a part of the K-20 curricula as a way to meet the need for a spatially literate workforce, while Solem, Cheung, and Schlemper had this to say about the need for geographic, GISci, and spatial education:

> "Our focus group and survey findings also confirm that many geographic and general skills are in high demand [in the workforce], yet the curriculum offered by academic departments may not be producing those skills at a level required to satisfy that need." (pg. 370)

And at a pragmatic level, Gersmehl (2008, pg. 3) provides a powerful rationale for the necessity of geographic and spatial education:

> "Geography is about the locations of things. Students (present and future business-people, voters, and elected officials) should learn how to choose locations and designs for buildings, roads, parks, election districts, and other things in ways that are fair, safe, efficient, and even beautiful."

Literature Review Summary

The human brain relies on several processes to aid in successful navigation: path integration, view dependent place recognition, and reorientation. Research supports the view that we are capable of viewing the world through both egocentric and allocentric frames of reference. These mental abilities allow us to gather and recall spatial information about the environments that we exist in. The evolution of our understanding of spatial microgenesis has been ongoing for many decades. In the early years, researchers in psychology discussed the nature of spatial knowledge, such as the existence of landmark knowledge and egocentric vs. allocentric knowledge, particularly in children. Later researchers in psychology and geography began to discuss more directly the process of gathering said knowledge. In the mid-1970s, Siegel and White proposed their theoretical framework for spatial microgenesis as a transition from landmark to route and then survey stages of knowledge. In 1998, Montello refined the dominant framework into his continuous framework, which circumvents the progression of Siegel and White, and says that survey-type knowledge exists from initial exposures to place.

Many researchers from the spatial sciences, particularly geography and GIScience, have called for a greater emphasis on spatial education in the American public schooling system, as this has been shown to improve the spatial reasoning skills of children, giving them a head start in a variety of areas of study. The STEM fields rely heavily on spatial thinking, so improving the state of geographic spatial education would provide larger benefits not only to geography, but to all of the sciences. This education also has the potential to improve the spatial microgenesis abilities of individuals in everyday life.

Chapter 3 - Methods

This research required the use of human participants, a computer lab with specialized software, and statistical analysis of the collected data. All of these elements were sourced from the Kansas State University campus. The participants were recruited from the student population, the computer lab was provided by the geography department's teaching lab, and statistical assistance was provided by the K-State Statistical Consulting Lab. Because human participants were a part of the research, Institutional Review Board approval was sought, but the study was declared exempt from IRB oversight.

Recruitment of Participants

Participants were recruited from two introductory undergraduate geography courses, as well as an advanced Geographic Information Science course (GEOG 708) at Kansas State in the fall semester of 2010. The introductory courses were GEOG100: World Regional Geography, taught by graduate teaching assistant Dr. Sohini Dutt, and GEOG200: Human Geography, taught by graduate teaching assistant and doctoral candidate Melissa Belz. The GIS II course was taught by Dr. Shawn Hutchinson. At each class, a short presentation was made explaining the thematic topic of the research, as well as a rough outline of what would be required of participants. Students were offered extra credit in their courses for participation in the research, contingent on the completion of all research tasks. The form of the extra credit varied between the three classes, but in each course, its value was approximately 10% of the total points available in the course. This amount of extra credit was deemed suitable compensation by the different teachers for what would eventually amount to approximately three hours of work. The signup sheets brought to the three classes collected 118 names with contact information. Two additional participants who were aware of the study volunteered outside of any course-specific recruitment at this same time for a total of 120.

Initial Surveys and Verifying Eligibility

The participants first took part in two initial surveys which were administered using Kansas State's in-house online survey software, Axio Survey. The two surveys were the Santa Barbara Sense of Direction Survey (SBSOD), and a general survey of previous spatial education; see Appendix A for complete copies of these survey questions (Hegarty, *et al.* 2002). Like its use in Ishikawa (2002), the SBSOD was used to collect a self-measure report of spatial abilities for participants, which returned a score anywhere from 15 to 105, with higher scores indicating better spatial abilities. Additionally, a survey of spatial education was administered to collect background information about participants and their history of education in geographic and spatial thought. The survey of spatial education also asked a crucial question relating to exposure to the virtual test environment, namely had the participant been exposed to the game *Left 4 Dead*. Prior exposure to the test environment could affect the results, and so participants who had played the game were eliminated from the subject pool. These participants who were removed were granted partial extra credit in their courses to reflect that they had made a good-will effort to participate, but would be unable to continue in the research. Twenty-two participants (18.3% of the total volunteer pool) had prior exposure to the game and were eliminated from participation.

Of the remaining 98 participants, only 69 (70.4%) completed the surveys. Of those 69 who completed the surveys, 58 (84.1%) completed all of the research tasks and received extra credit for their courses. Some had scheduling issues that prevented them from participating (and received partial extra credit), others simply did not respond to communications following the initial surveys and received no compensation.

Organization of Participants

The 58 participants were divided into three groups. The first group of 20 participants received no map exposure before any session, and was labeled the Red Group. A group of 13 was exposed to a map of the virtual environment for one minute prior to exploring in each session, and was labeled the Blue Group. A final group of 25 participants did not receive map exposure before session one, but viewed the map in the second and third sessions; this final group was the Yellow Group.

Preparing the Virtual Environment

The commercial game *Left 4 Dead* served as the virtual environment used for data collection. This game comes bundled with an editing tool (the *Hammer World Editor*) that allows users to create and modify their own game content. It also allows users to modify the content that comes pre-authored with the game, which is realistic in the design and feature high quality art assets for an immersive experience. For this research, the first stage in the game campaign 'Blood Harvest' (the game is zombie survival themed, hence the name) was chosen. The stage involved a twisting path with wider open areas and multiple distinct landmarks. Since the stage takes place in Allegheny National Forest (it is not modeled after the real layout of the national forest), the virtual environment is dominated by trees and natural features; this type of environment helps the man-made structures to stand out for use as landmarks. An example of one of the landmarks that was used, a yellow car, can be seen in **Figure 3.1**. This environment takes place largely on one plane of elevation. While there are changes in elevation, understanding the layout does not require spatial translations like those necessary when one changes floors in a building. Since this kind of spatial translation can be difficult, (and given that participants were asked to draw sketch maps) keeping the environment constrained to one level helped to reduce confusion (Richardson, Montello, Hegarty 1999; Wang and Brockmole 2003). The complete map with all eight landmarks can be seen in **Figure 3.2**.

Figure 3.1 – An example of one of the landmarks in the environment, the yellow car which is the second landmark (see Appendix C for views of the rest of the landmarks).

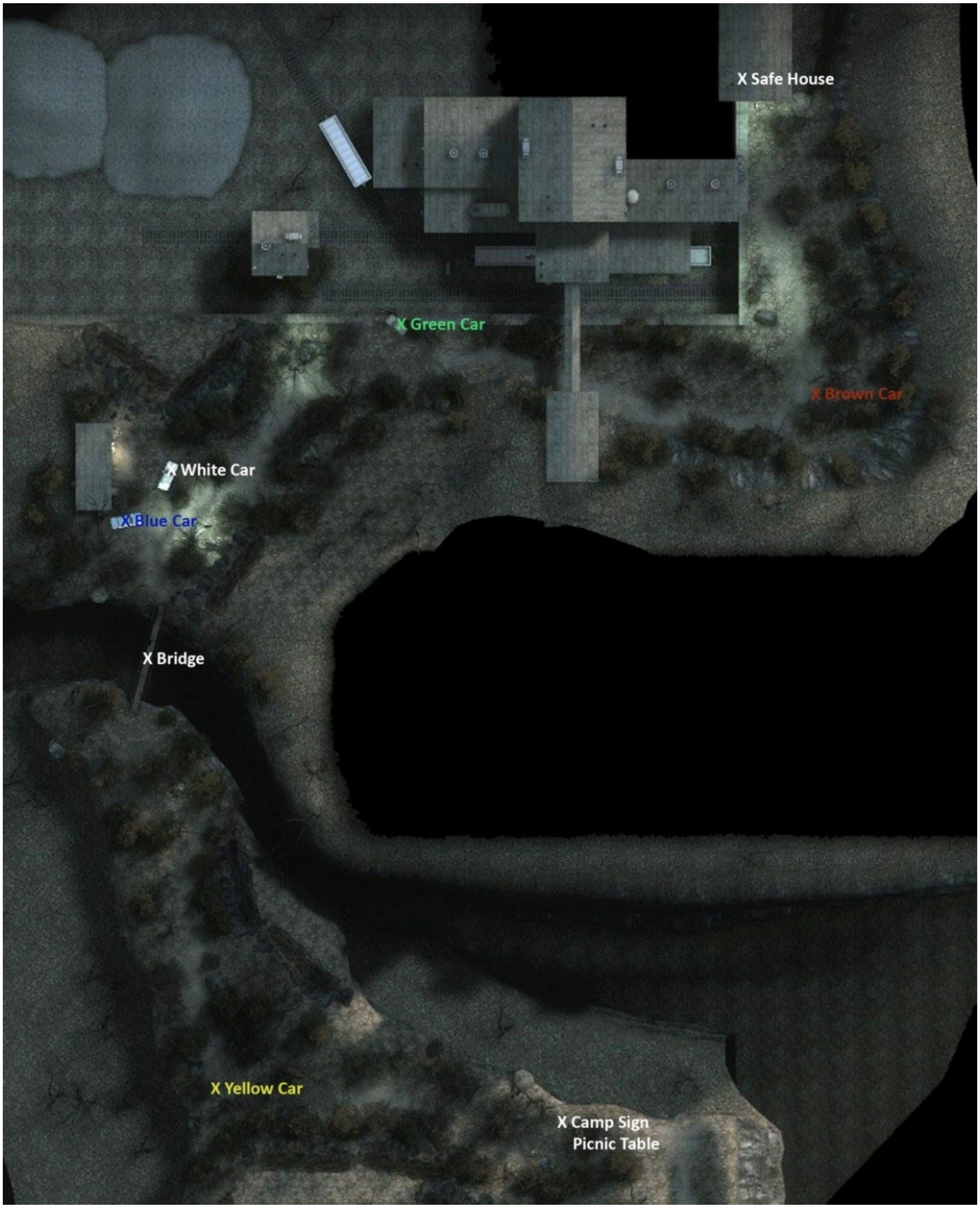


Figure 3.2 – The reference map showing the positions of the eight landmarks.

Because the game involves shooting zombies with various weapons and leading a team of humans to safety, modifications were necessary to make the environment suitable for research. Using the *Hammer World Editor*, all items related to gameplay were removed. Stockpiles of virtual weapons, ammo, first-aid kits, and explosives were removed; likewise, all ‘spawn points’ which the game uses to generate enemy zombies were removed so that participants in the research would be allowed to explore without interference. Other visual elements, such as victims of the zombie apocalypse were removed as well. Essentially, all of the elements that make *Left 4 Dead* a game were removed from the virtual environment.

Without zombies or guns, it was much easier to observe the spatial layout of the environment unhindered, but dangers to the participants’ digital avatars still remained. The environment features some steep drops at several points; these ledges had to be barricaded so that participants could not ‘kill’ their avatars by falling from great heights. In cases where the game layout had left holes in fences, new sections of fence were created to fill the gaps; in other areas, invisible barriers were erected to prevent participants from falling to their deaths. Once the modifications to the environment were complete, a copy of the modified stage was loaded on to each of the computers in the geography department’s teaching laboratory.

Preparing the Data Collection Facilities

Prior to data collection, the computers in the teaching lab were prepared for the research (See **Figure 3.3** for a view of the testing facilities). The computers in the lab have multiple hardware specifications, but all have at least a dual-core processor, 3 gigabytes of RAM, and a 3D video capable of running the *Left 4 Dead* software at a visual resolution of 1024x768 at 30 frames per second. The computers all have dual 19” 4:3 LCD monitors, although the virtual environment was only displayed on one monitor per computer. Each computer has the PC gaming platform *Steam* installed, as it is required to run *Left 4 Dead*. In addition to the standard computer, monitor, mouse, and keyboard setups, participants were provided with a set of headphones to provide audio inside the virtual environment. *Left 4 Dead* provides environmental sounds such as wind, footfalls, and other ambient audio that help immerse users in the environment.

Figure 3.3 – The testing facility used to collect data. A fourth table of computers is out of view to the left of the image. The students in this image were not part of the data collection.

Collecting the Data

After juggling schedules with participants, data collection began in the geography department's teaching computer lab. To begin the first session, participants in all groups were instructed to load the game, and then load a 'control' environment in which they were allowed to become comfortable with the method of controlling motion in the virtual environment. In order to load non-standard game maps, the 'developer console' was used. This in-game command line prompt is activated by pushing the tilde key (the ~ symbol at the top left of a standard US keyboard). Once this control environment was loaded for all participants, verbal instructions were provided as to the use of the mouse and keyboard for movement. The W, A, S, & D keys control part of the player's avatar motion, with W & S moving forward and backward respectively, and A & D causing the avatar to sidestep to the left and right respectively. The spacebar allows the avatar to jump, and the E key opens and closes doors. The mouse controls the avatar's head motions as well as rotating the body to the left and right. Pushing the mouse forward will cause the player to look up, and backward will look down. See **Figure 3.4** for a visual reference to the control mechanisms. Although participants were given as much time as necessary to become comfortable with the controls for moving the avatar, this process took fewer than five minutes.

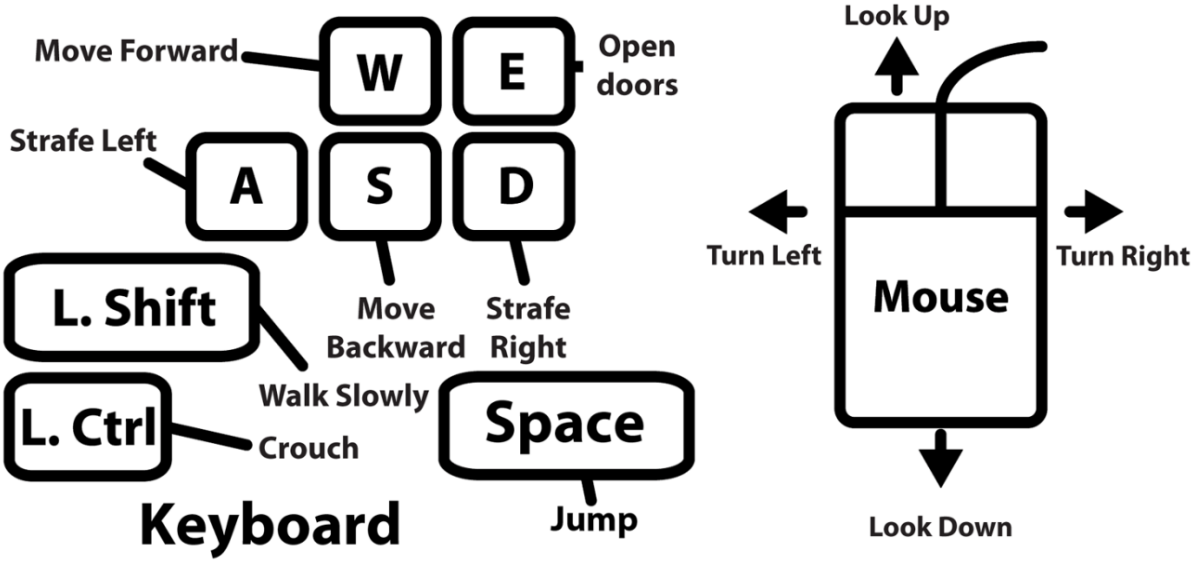


Figure 3.4 – The control layout for *Left 4 Dead*.

Participants were then instructed to load the test virtual environment by typing the map's name in the developer console. They were instructed to not touch the controls until the timer was started; once all computers had loaded the level, participants were told to begin exploring the environment and the timer was started. They were instructed to remember the locations of eight landmarks in the environment; five cars, each a different color; a National Forest sign next to a picnic table; a rope bridge; and a 'safe room' which has a red metal door with iron bars over the window (See **Figure 3.2** for an image of the yellow car, and **Appendix C** for images of all eight landmarks). After ten minutes of exploration, participants exited the game.

Measures of Spatial Recall Ability

Following ten minutes of exploration in the virtual environment, each participant took part in three tests that measured spatial recall ability: a direction estimation task, a distance estimation task, and a sketch map drawing task. Objectively measuring an individual's spatial knowledge can be difficult, since factors such as drawing ability can potentially obscure one's understanding of space. For this dissertation, the tasks and their implementation were derived largely from the work of Toru Ishikawa (2002; Ishikawa and Montello 2006). The same tasks or variations of them are commonly used for measuring spatial knowledge in other research as well

(Thorndyke and Hayes-Roth 1982; Moeser 1988; Wang 1999; Wang 2004; Wan, Wang, and Crowell 2009). The three tasks followed participant exploration of the virtual environment by a few minutes.

First was the direction task. Each participant received an 8.5x11" piece of paper with six figures on it of the same design that is shown in **Figure 3.5**. Participants were instructed that they would be presented with pairs of landmarks drawn from the eight in the virtual environment, and to envision that they were standing on the X in the center of the circle. The arrow at the top of the circle would be pointing at the first landmark in the pair; they would then be asked to draw an arrow pointing in the direction of the second landmark in the pair. The furniture in the computer lab was used as a real-world example of how to fill out the forms to insure that participants understood how to complete the task. Following these instructions, an image of a landmark from the virtual environment was displayed on a projector screen (the screen can be seen on the back wall in **Figure 3.3**) and identified as the first landmark in the pair, and the second landmark in the pair was verbally identified. In each of the three sessions, participants matched six pairs of landmarks in this way. Each landmark would remain on the screen until all participants had had enough time to complete the pair. Once all six pairs had been finished, the forms were collected from the participants. The procedures and execution of the direction estimation task was consistent with that found in earlier experiments (Ishikawa 2002; Ishikawa and Montello 2006). While the landmark pairs changed from session to session, the pairs remained consistent between the three groups, *e.g.*, the Red Group saw the same pairs of landmarks as the Blue and Yellow groups in session one.

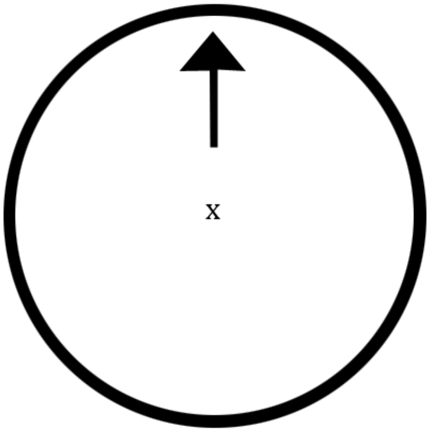
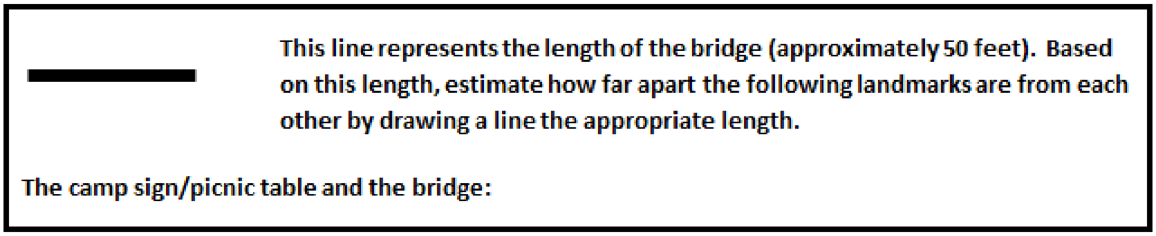


Figure 3.5 – An example of the direction estimation figure.



This line represents the length of the bridge (approximately 50 feet). Based on this length, estimate how far apart the following landmarks are from each other by drawing a line the appropriate length.

The camp sign/picnic table and the bridge:

Figure 3.6 – An example of the distance estimation form, the instructions and reference line are at the top, and an example pair of landmarks at the bottom. The full form included seven more landmark pairs in addition to the example pair above.

The distance estimation task was also completed on an 8.5x11" piece of paper by each participant. Each paper had a list of eight pairs of landmarks and a black scale bar at the top of the page (See **Figure 3.6** for an example of the distance estimation form). Participants were asked to imagine that the bar represented the length of the rope bridge in the game environment, and that the bridge's length was approximately 50 feet. For each pair of landmarks, they were asked to draw a line that represented the distance between the two, using the black scale bar's length as a guide. This task was also administered in a manner consistent with previous research (Ishikawa 2002; Ishikawa and Montello 2006). The landmark pairs used for this task were identical for each of the three subject groups. Once all participants were done with the distance estimation task, the papers were collected and the group moved on to the final task.

The third, and final, task was to draw a sketch map of the virtual environment that had been explored. Following the lead of Billinghurst and Weghorst (1995), each participant received a blank 8.5x11" piece of paper and was instructed to draw a map including the eight landmarks, but no further instructions were provided regarding how the map should be drawn. Some participants asked if they should include specific features from the environment on the map, and as an attempt to not influence the output of the participants the response was always "You may draw anything you feel should be included." An example of one of the sketch maps that was submitted can be seen in **Figure 3.7**.

These procedures were repeated over the course of three sessions, each session one week apart. The number of sessions chosen was based on the work of Ishikawa and Montello (2006), which followed participants in similar situations over the course of ten sessions. As with similar research (*e.g.* Gärling *et al.* 1981), they reported that beyond initial exposure, little improvement in abilities was detected in later sessions (which is problematic for both frameworks, since they state that knowledge will grow over time). Based on this understanding, the sessions were limited to three, as it was assumed that change in performance would be unlikely beyond a third experimental session. Following the completion of three full sessions, the participants' names were passed back to their instructors to ensure that they were compensated with extra credit.

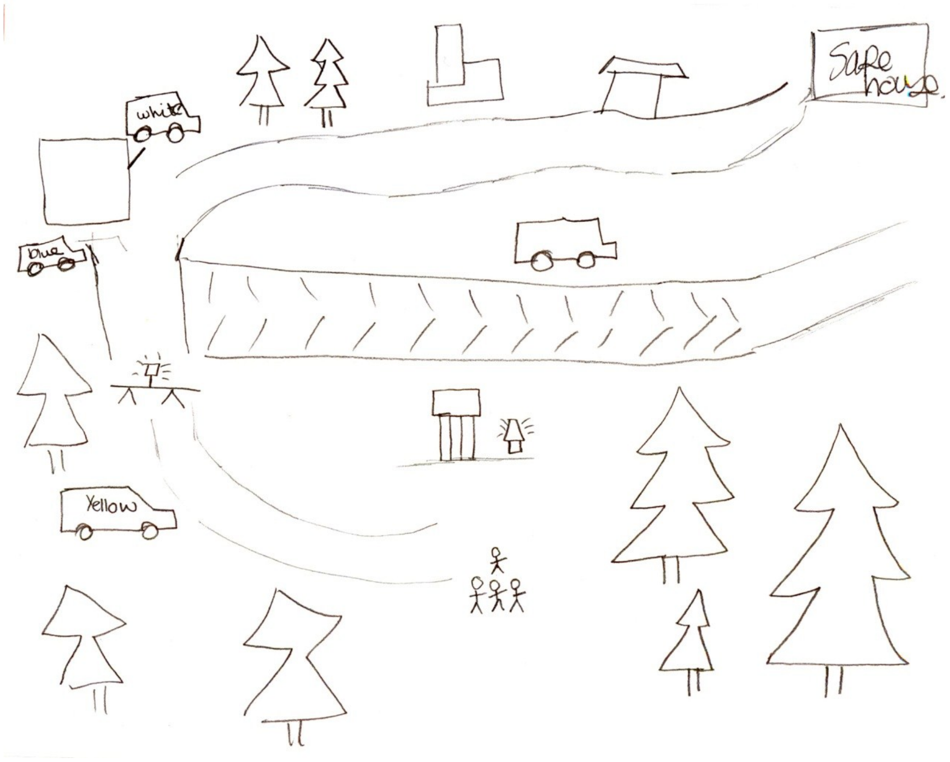


Figure 3.7 – An example of a sketch map submitted by a participant from the Red Group, session one.

Transcribing the Results

Since data collected from the participants was largely on paper, transcribing it into a digital form was necessary for analysis. The initial surveys were completed online using the Axio Survey tools provided by Kansas State, meaning that these results were already in a digital format, but the experiment output from the direction, distance, and sketch map tasks required labor-intensive approaches to digitize. The direction estimation task was measured in degrees and recorded in a spreadsheet. Each landmark pair's actual direction value was listed, followed by the individual's reported value, the absolute error between the two, and the percentage of error. Recording error in degrees was difficult, since degrees are modulo 360. This manifested itself in several instances where, for example, the actual direction of the second landmark in a pair was at 354° and a participant reported the value as 10°. A simple subtraction would say that the estimate was off by 344°, when in fact the value would only be off by 16°. In order to get an accurate estimate of the error of participants' values, a spreadsheet formula was created to calculate the actual error and is as follows: IF ([reported error] > 180 THEN 360 - [reported error], IF ([reported error] < 180 THEN [reported error])). This statement ensures that the error recorded in the spreadsheet will always remain under 180, which is the furthest away from the correct heading that an estimate could possibly be. Following the measurements of error for the six landmark pairs in the spreadsheet, a formula summed the error in degrees for all pairs, as well as a column summing the total percent error for each participant.

The distance estimation task results were measured in centimeters with the use of a standard ruler. The lengths of reported lines were measured and recorded in a spreadsheet. Some participants drew hash marks on their lines, and it was assumed that each hash mark represented a 'bridge length' of 50 feet even if the marks were not perfectly spaced on the page. The spreadsheet was used to record not only the participant-generated measurements, but also the true distance measures made by measuring the official map to get the distance between landmark pairs in cm. These two columns were followed by the absolute value of the error (since participants could over- or undershoot the mark), as well as the percent error. Following the values for all eight landmark pairs, a formula summed the error in cm for the session, as well as a total percentage error for each participant.

The map drawing task provided a challenge in how to quantify error. Some previous work has utilized a qualitative assessment approach, using multiple researchers to rank the quality of a given map based on a visual analysis (Billinghurst and Weghorst 1995). Others employed a more quantitative approach, using bi-dimensional regression (Ishikawa 2002; Ishikawa and Montello 2006). A semi-automated process was desired for an unbiased, consistent, and fast analysis. After some investigation, the process of image rectification as used in a Geographic Information Systems context was selected as the method for analyzing maps. In order to do so however, the maps first had to be converted to a proper format. First, the paper maps were scanned into digital images. The scanned images were 'cleaned' by adjusting the brightness and contrast and also to remove empty white space on the page (not all participants used the entire page to complete their maps). Participants' maps were rotated so that 'north' was at the top of the images (When looking at the official map, **Figure 3.1**, the top of the image was considered to be north). Maps were then resized so that the digital images were the same resolution as the official map, either in width or height, depending on the orientation of the participant maps. This resizing process was done in order to reduce error in the rectifying process related to image sizes and the scales at which maps were drawn. See **Figure 3.8** for a 'before and after' of a map being processed.

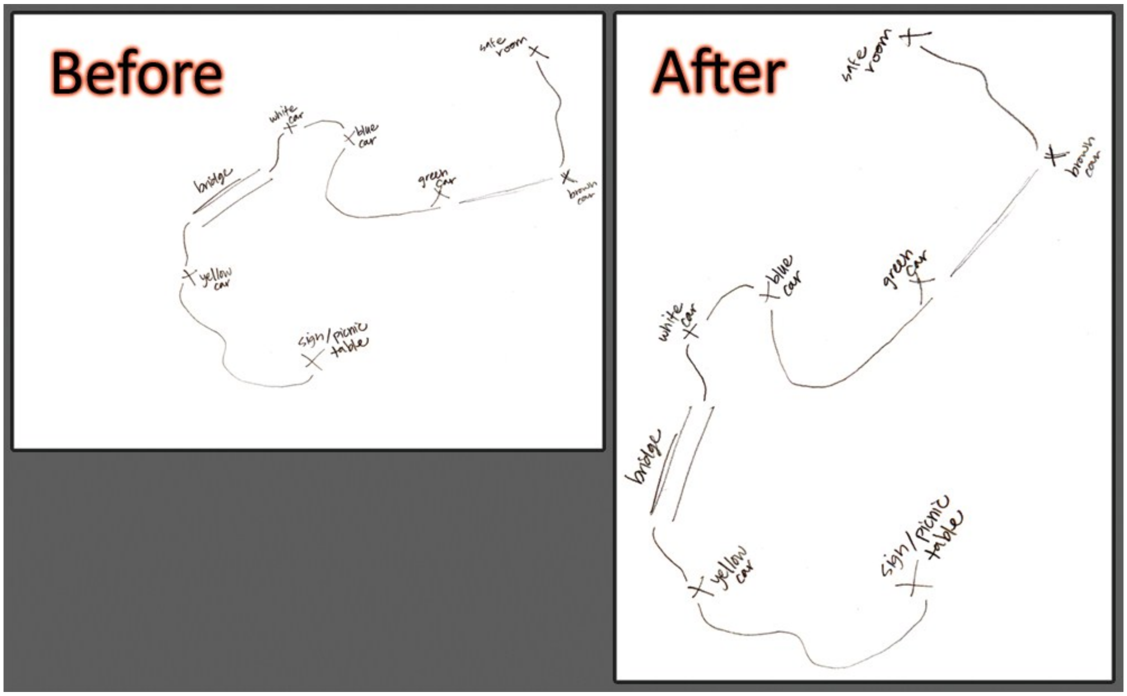
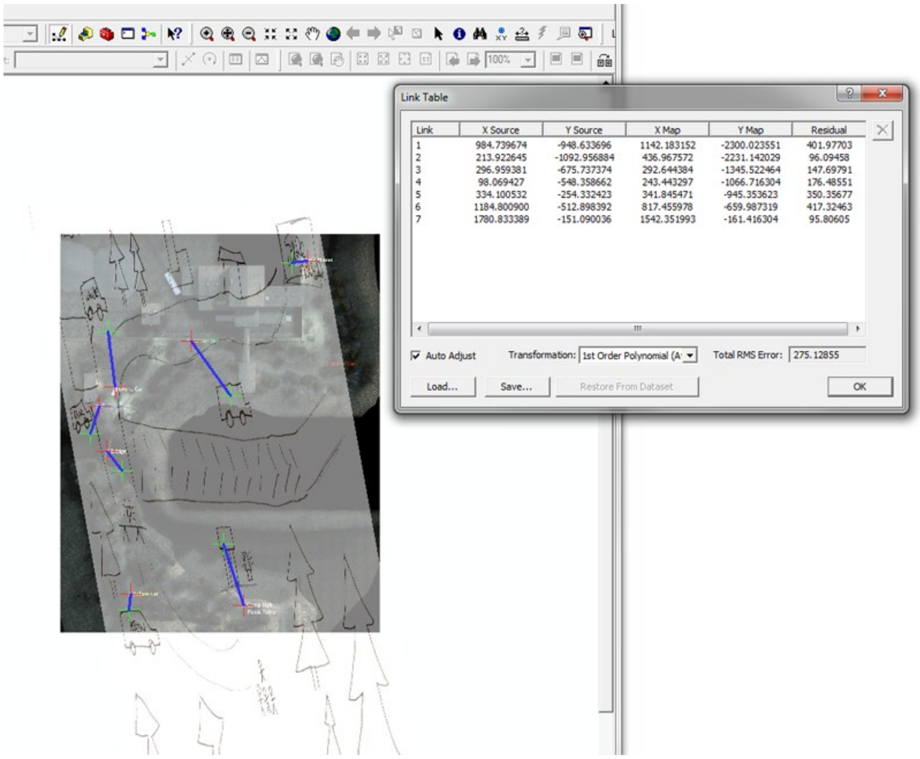


Figure 3.8 – A participant sketch map before and after being prepared for rectification.

After the 174 participant maps were prepared (58 participant maps across three sessions), the official map and the participant maps were loaded into the ArcGIS 9.3.1 software (ESRI, Redlands, CA). Typically, image-to-image rectification (referred to as 'georeferencing' in ArcGIS 9.3.1) involves taking control points with known geographic coordinates (the source) and tying them to the target image in order to 'transfer' a projected coordinate system to the target image. During the process, error is calculated for each control point, essentially indicating how far from the correct location each point is. The official map shows an accurate description of the spatial layout of the area, which can then be compared to the participant maps. The root mean square (RMS) error that is returned after rectifying an image is the RMS of residual error for all control points combined, which can be used as a measure of how accurate the participant maps are when compared to the official map (ArcGIS Desktop Help 2009). The eight landmarks from the official game map were used as the control points, and each were used to rectify each participant's map. The control points were selected in order from the starting area to the 'final' landmark in the environment (the camp sign with picnic table and the red metal safe room door, respectively). See **Figure 3.9** for a map in the process of rectification. For maps that had high levels of distortion (such as landmarks wildly out of order), the rectifying process was impossible to complete as the map became so distorted that it was unable to visually interpret.



Link	X Source	Y Source	X Map	Y Map	Residual
1	984.739674	-948.633696	1142.183152	-2300.023551	401.97703
2	213.922645	-1092.956884	436.967572	-2231.142029	96.09458
3	296.959381	-675.737374	292.644384	-1345.522464	147.69791
4	98.069427	-548.358662	243.443297	-1066.716304	176.48551
5	334.100532	-254.332423	341.845471	-945.353623	350.35677
6	1184.800900	-512.898392	817.455978	-659.987319	417.32463
7	1780.833389	-151.090036	1542.351993	-161.416304	95.80605

☑ Auto Adjust

Transformation: 1st Order Polynomial (A

Total RMS Error: 275.12855

Figure 3.9 – The ArcGIS software rectifying a participant map.

Maps with this high level of distortion received a 550 for their RMS score (100% RMS Error). For comparison, maps with low levels of distortion received scores of 50-100 (9.1-18.2% RMS Error), while maps with high error (but still capable of being rectified) fell within the range of 400-540 (72.7-98.2% RMS Error). It is believed that using the RMS score generated by ArcGIS as a measure of sketch map error is a novel method of quantitatively measuring sketch map quality.

In addition to the rectifying process, maps were examined for other qualitative criteria, including the number of landmarks included, the number of significant objects in the environment included (including the eight landmarks). If a participant did not include all eight of the objects, they received a negative score for each landmark missed, which factored into this calculation. The maps were also qualitatively classified as landmark-, route-, or survey-type maps. The question of survey-, route-, or landmark-type map was answered by having three researchers categorize the maps, in a similar process as that used by Billinghurst and Weghorst (1995). As an example, take the sketch map in **Figure 3.7**. This map falls into the survey-type of representation, includes seven of the eight landmarks, but also includes four extra objects; three buildings and a second picnic table (individual trees were not counted as significant objects).

Analyzing the Data

To test tenet one, 'there is no stage of pure landmark or route knowledge', maps from participants in the Red and Yellow groups in the first session (groups with no map exposure prior to the first exploration of the virtual environment) were categorized as landmark, route, survey, or other map types. Three researchers who were familiar with virtual environments and had been exposed to the actual layout of the environment were employed to help with this qualitative categorization. These researchers' categorizations were calibrated with sample maps (not the same maps used for testing tenet one) until their responses were indistinguishable from one another. Because of small sample sizes and the fact that the RMS error scores were not normally distributed within the categories of maps, the nonparametric Mann-Whitney U was chosen as the statistical test.

For tenet two, 'as experience grows with a place, so too does metrically-scaled spatial knowledge', sketch maps were taken from the Red group from sessions one and three. Data from the direction, distance, and sketch map tasks were then compared between the first and last sessions. Again, due to small sample sizes and a non-normal distribution of error scores, the Mann-Whitney U was employed for analysis.

Tenet four, 'individuals with similar amounts of exposure to a place will differ in the extent and accuracy of their spatial knowledge', necessarily requires that groups of participants with similar exposures would be compared. In order to do this, each task/session/group combination (24 sets of data total) were measured for the coefficient of variation within them. The results of all of these statistical analyses can be found in following chapter.

Methods Summary

Participants were recruited from undergraduate geography classes as well as an advanced GIS course at K-State. Participants completed the SBSOD survey of spatial ability, and a survey of spatial educational history and participation eligibility. Those who were eligible were divided into three groups, the Red group who were never exposed to a map of the virtual environment, the Blue group, who saw the map prior to each session, and the Yellow group, who saw the map only prior to the second and third sessions. The groups were exposed to the novel virtual environment for 10 minutes in each of three sessions scheduled one week apart and instructed to remember the location of eight distinct landmarks in the environment. Following each exploration of the virtual environment, participants were assigned three spatial tasks to complete including a direction estimation task, a distance estimation task, and a sketch map task.

The data gathered from these three tasks was then transcribed to a digital form and analyzed statistically to test the three hypotheses related to the two theoretical frameworks of spatial microgenesis that were being compared. The quantitative measurement of sketch map quality was recorded using ArcGIS 9.3.1 software's image rectification tool. It is believed that this is a novel approach to quantitatively measuring sketch map quality. For the tests related to tenets one and two, small sample sizes and non-normal distributions led to the use of the Mann-Whitney U test. For tenet four, the coefficient of variation scores were recorded for 24 distinct groupings of participants.

Chapter 4 - Results

The primary research question of this dissertation is whether or not Montello's continuous theoretical framework does a better job of explaining spatial microgenesis than Siegel and White's dominant framework. Three of the tenets of the continuous framework were tested to determine their validity. For testing tenet one (no stage of pure landmark or route knowledge will exist), the hypothesis is that no pure landmark or route knowledge will exist following an initial exposure to a novel environment, with the null hypothesis being that evidence of landmark and route knowledge as described by the dominant framework will exist. For tenet two (as experience with place grows, so too does knowledge), the hypothesis is that a statistically significant decrease in error will exist between the first and final sessions, the null hypothesis being that no statistically significant evidence of improvement will be found. And for tenet four (individuals with similar amounts of exposure to place will differ in their knowledge), the hypothesis is that variance will exist in the performance of groupings with similar levels of exposure. The null hypothesis for this tenet is that no variation will be found within groupings of individuals' performance. In order to test these hypotheses, it was necessary to measure participants' spatial recall abilities after exposing them to a novel environment over the course of three sessions. Participants were split into three groups: the Red Group who received no map exposure prior to exposure to the novel environment, the Blue Group, who received map exposure prior to all three sessions' exposure, and the Yellow Group, who received map exposure prior to the second and third sessions. Each of the participants also took part in two surveys prior to exposure to either the map or novel environment in order to measure their level of spatial ability and educational history regarding spatial thinking.

Survey Results

The initial surveys given to the participants measured their level of spatial ability (the Santa Barbara Sense of Direction or SBSOD survey) and their level of education regarding typical spatial activities such as reading maps or navigating using a compass or GPS unit (See Appendix A for full copies of the surveys). The SBSOD survey is a self-report measure of spatial ability made up of fifteen statements about spatial ability. Participants indicate their level of agreement with the statements on a seven-point Likert Scale, and at the end their scores are summed. This gives a range of potential scores from 15 to 105, with higher scores indicating higher levels of spatial ability. Reported scores ranged from 43 to 95, with a mean score of 72.1 and a normally shaped curve to the data.

The survey of spatial education found that few of the participants had received formal education in spatial activities in an academic setting. The question with the highest positive response, at 39.6% (including the 24% of participants who were recruited directly from a GIS course), was “Have you ever received training in map reading?” Removing the GIS students, this means that only 15.6% of students enrolled in introductory level college geography courses have had any formal education in regards to reading maps. The responses to the other questions were considerably lower, especially when the GIS students were removed from the data. This indicates that the general population of students enrolled in introductory geography courses has a distinct lack of formal education regarding basic spatial activities such as navigation, compass reading, and use of GPS technologies. In regards to the discussion of spatial education in the literature review, this is evidence that K-12 education is failing to provide students with valuable knowledge of geographic and spatial topics.

Tenet One – There is no stage of pure landmark or route knowledge

If the continuous framework of spatial microgenesis is correct, all sketch maps will have some form of metric knowledge contained within them, even if it is a poor level of knowledge. In order to determine if a stage of pure landmark or route knowledge (that is to say knowledge without metric information) existed in any of the sketch maps, the 44 session one sketch maps from the Red and Yellow Groups (no map exposure in session one) were qualitatively categorized into four groups: landmark, route, survey, and other. The first three categories fit neatly into the descriptions provided by the dominant framework. Landmark maps contain nothing but, route maps are linear pathways strung between landmarks, and survey maps are more complete and ‘map like’, including much more supplementary spatial information such as the shapes of the land areas the route covered. Maps in the ‘other’ category could not be easily categorized, either because of a lack of spatial information on the page or because they were not maps in any traditional sense of the word. **Table 4.1** shows information about the map categories, including the number of maps that fell into each category, the average % RMS error for each, and the mean Santa Barbara Sense of Direction scores of the participants represented in each category. **Figure 4.1** shows a boxplot of the % RMS error score distributions.

Total	Landmark	Route	Survey	Other
44 maps	4 maps – 9.1%	21 maps – 47.7%	15 maps – 34.1%	4 maps – 9.1%
61.2 AVG %Error	62.8 AVG %Error	58.3 AVG %Error	57.0 AVG %Error	90.6 AVG %Error
72.1 AVG SBSOD Score	70.3 AVG SBSOD Score	72.4 AVG SBSOD Score	73.1 AVG SBSOD Score	68.5 AVG SBSOD Score

Table 4.1 – Sketch Map Information following first exposure to the novel environment.

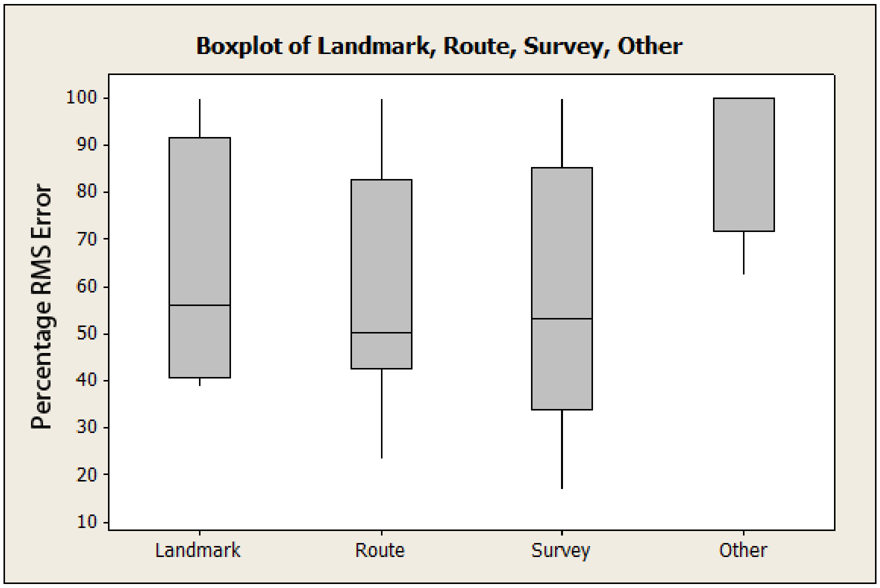


Figure 4.1 – Boxplot showing the distribution of RMS error scores across the four categories of sketch maps.

Four of the forty-four maps (9.1%) fell into the landmark category, examples of which can be seen in **Figures 4.2 & 4.3**. The mean error score for landmark maps was slightly higher than the overall average because of the combination of small sample size and a 100% error score on one of the maps (recall that 550 is the upper end of the range for RMS scores given to maps with little to no displayed spatial knowledge and counts as 100% error for the calculations). The other three maps had less extreme % RMS error scores at 38.9, 46.6, and 65.6. Despite having an overall higher average % RMS error score, it is clear that most of the maps in this category still represent metrically-scaled spatial knowledge of the environment (See **Figure 4.2**). On average, the landmark maps included one extra object beyond the required eight primary landmarks. The average SBSOD score of the four participants with landmark maps is slightly lower than the overall mean, although this score is also brought down by one participant in the group with a score of 51 (responsible for the 100% error map). The 100% error map in the landmark category (**Figure 4.3**) comes the closest to a 'pure' landmark map, since it is a jumble of landmarks placed seemingly at random. Given the description of landmark knowledge provided by the dominant framework, this map technically fits the requirements, although the landmarks are arranged in such a way as to indicate that the participant understood, to a small degree, the metric layout of the environment. That less than 10% of the total map output fell into the landmark category after the initial exposure to the environment and that only one of them (0.22% of the total population) could be potentially considered a 'pure' landmark map suggests that landmark knowledge probably does not commonly exist (if at all) as described by the dominant framework. In agreement with the results of Ishikawa and Montello (2006), people with normal levels of spatial ability are generally able to move beyond the landmark stage with little exposure to an environment.

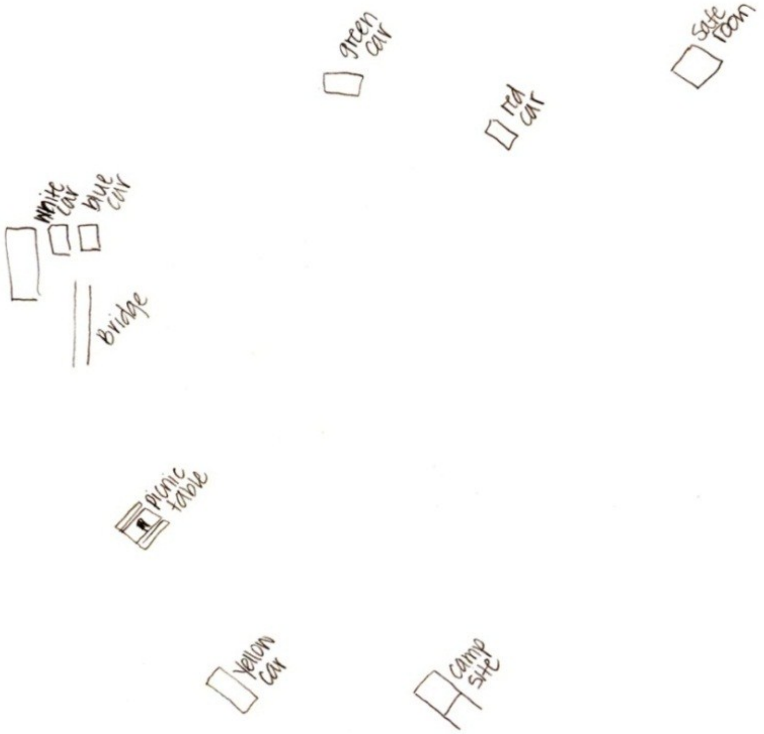


Figure 4.2 – An example of a sketch map that fits into the landmark category of spatial knowledge. Despite not including detail beyond the landmarks, it is clear that configurational knowledge of the layout exists in this map.

Figure 4.3 – Another example of a landmark map. This map has a poor RMS score of 550 (100% RMS error), since the landmarks appear to be randomly spaced on the page. In a sense, this map represents the closest to a pure landmark map that was submitted.

Twenty-one of the forty-four maps (47.7%) were considered route maps, and examples can be seen in **Figures 4.4 & 4.5**. This was the largest category of sketch maps in the Red and Yellow Groups' first session output. These types of maps generally had low % RMS error, close to that found in the survey category maps. Route maps also out-performed landmark maps (but not survey maps) in terms of the extra object count, with an average of 1.238 extra objects per map. Again, for the most part, these maps do not appear to represent the idea of a route map as described by Siegel and White's dominant framework. One map (seen in **Figure 4.4**) approaches the dominant framework's route ideal, "a one-dimensional chain of landmarks and actions" (Ishikawa and Montello 2006, pg. 123). The producer of this sketch map had a SBSOD score of 64, below the median score of all participants. Despite the linear shape, the map still has a small amount of metric spatial knowledge, as landmarks are placed to the right or left of the linear path indicating turns required to reach the landmarks. While this map comes to closest to describing the dominant framework's stages of knowledge, it still probably does not count as 'pure' route knowledge. The other twenty route-style sketch maps contained more metrically-scaled knowledge of the space, a typical example of which can be seen in **Figure 4.5**. Again, the fact that only one of the maps approaches a state of 'pure' landmark knowledge strongly indicates that metric knowledge is present from very early on, consistent with the continuous framework's first tenet.

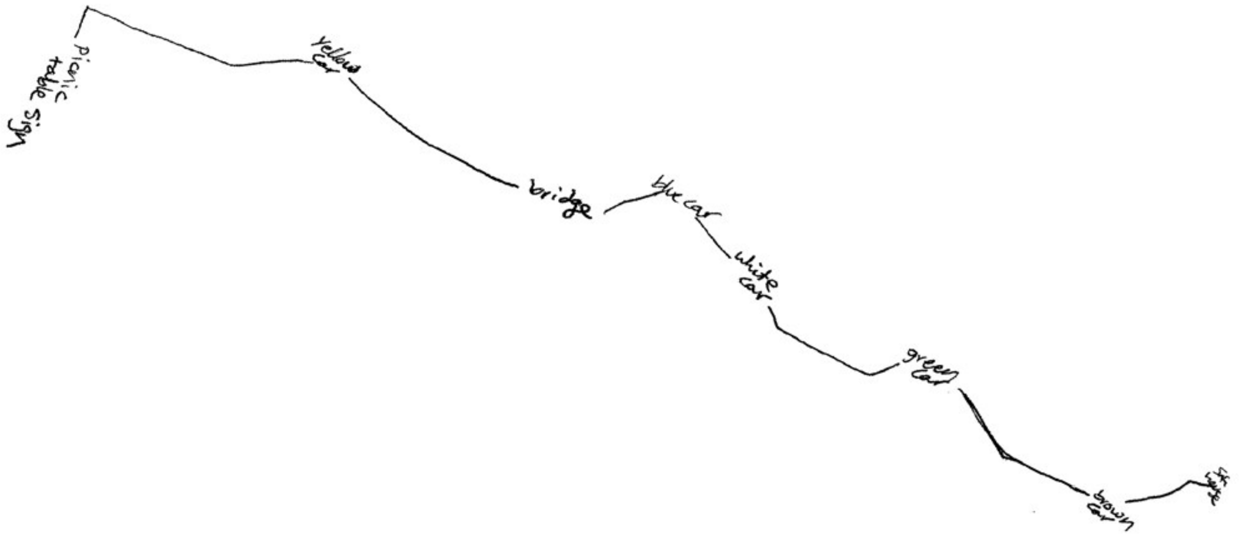


Figure 4.4 – An example of a sketch map that fits into the route category of spatial knowledge. This particular map was far more linear in its configurational layout that most route maps. This map is the closest example to a pure route map that was created, although it still contains metric information and cannot be considered a 'pure' route map.

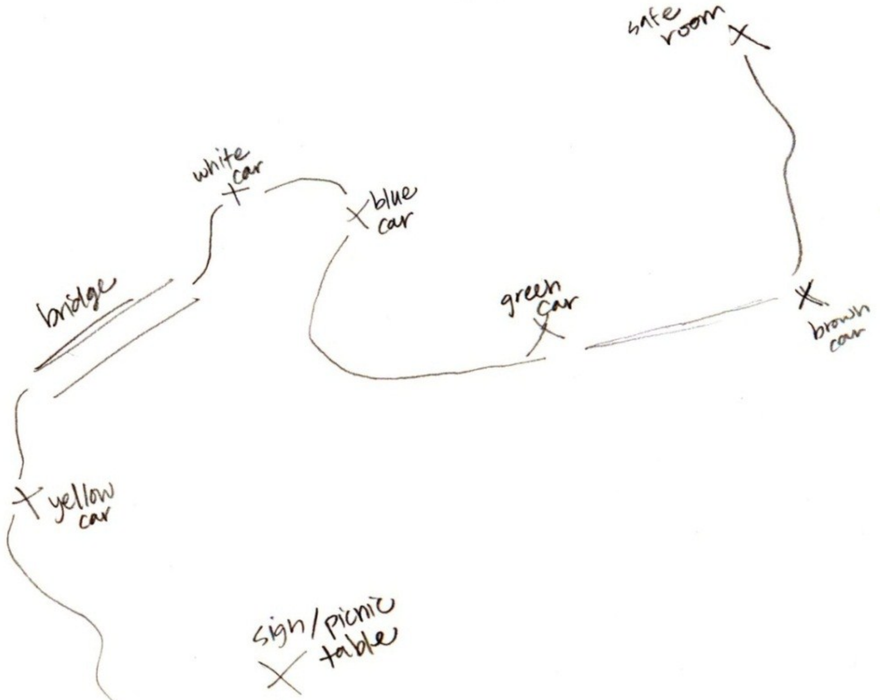


Figure 4.5 – Another example of a sketch map that fits into the route category of spatial knowledge, this one more typical of the output of the participants.

Fifteen of the maps (34.1%) fell into the survey category, examples of which can be seen in **Figures 4.6 & 4.7**. These maps had the lowest % RMS error, slightly lower than that of the route-style maps; however, the metric error in the spatial configuration of a sketch map is only one facet of their evaluation. While the survey style maps were not significantly more accurate than landmark or route maps in terms of their average % RMS error, they generally had a higher level of spatial understanding of the environment, in part because they tended to be the most ‘map-like’, including far more context in the map layout and inclusion of cartographic map elements such as scale bars and north arrows (Dent, Torguson, and Hodler 2009).

It is obvious that the survey category was more successful in including extra objects on their maps beyond the required eight landmarks, with 3.2 extra objects on average, far higher than the landmark category’s 1 extra, or route’s 1.238 extra. **Figure 4.6** is an example of a map with many extra details above and beyond the eight landmarks. This would make sense according to the dominant framework, since one’s spatial knowledge should be quite large by the time it reaches the survey stage. That being said, the dominant framework suggests that this high level of spatial knowledge should not be possible after such a short period of exposure to the environment, unlike the continuous framework which allows for this possibility.

Some participants went beyond simply adding extra objects, including extra details such as north arrows, scale bars, and slope estimates for the terrain they navigated (see **Figure 4.7**; these ‘map elements’ were not included in the extra object count). This is explained by the background in GIS and cartography that some of the participants had, and while it did not necessarily improve their metric spatial recall, it was an interesting inclusion that helped to improve the overall quality of the maps from a qualitative standpoint. As previously mentioned, the % RMS error and completeness of these maps runs counter to the progression described by the dominant framework. These fifteen maps were drawn at what can be considered survey-level knowledge (the lowest average RMS errors and the highest information density) with merely ten minutes of exposure, indicating that for some participants, the landmark and route stages of map knowledge can be either bypassed or learned so quickly as to make the progression of knowledge described by the dominant framework largely irrelevant.

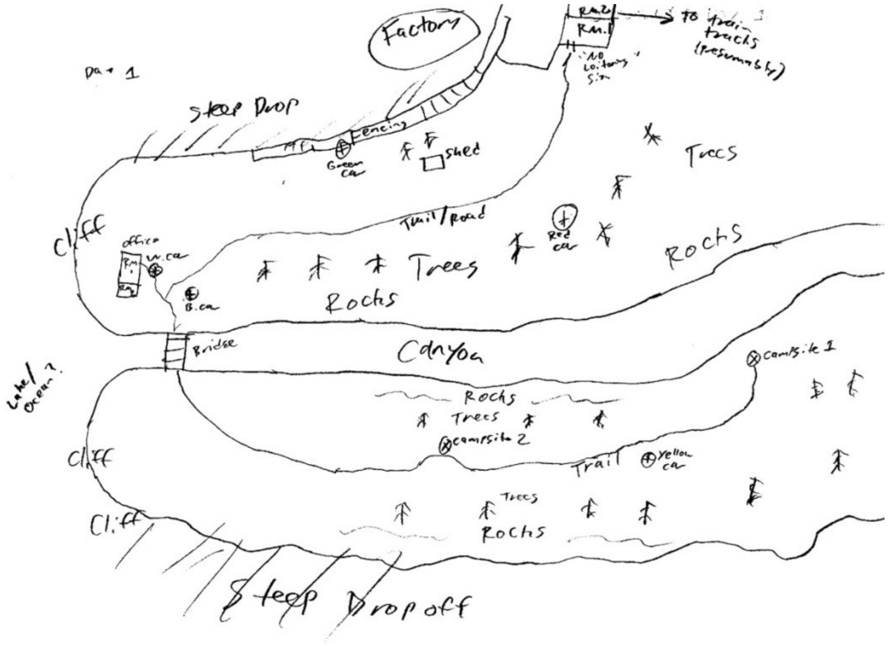


Figure 4.6 – An example of a sketch map that fits into the survey category of spatial knowledge. Survey-type maps included not only the landmarks and the route, but a more complete map-like view of the environment. Note the density of information included on this map, which was unusual for the participants.

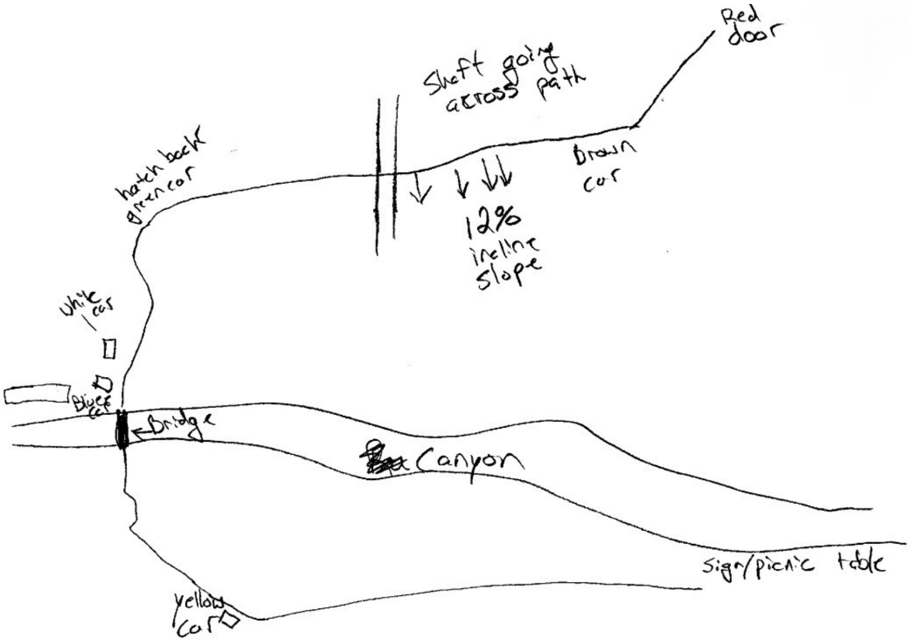


Figure 4.7 – An example of a survey-type map that includes ancillary information, in this case an estimate of the slope of the terrain.

Four of the maps fell into the other category, and examples can be seen in **Figures 4.8 & 4.9**. This category did much worse than the other three in terms of % RMS error as can be seen in **Table 4.1** as well as **Figure 4.1**. They also scored poorly in terms of the number of significant objects on the maps, with an average of -2.25 extra objects (meaning that most of the maps did not include all of the eight primary landmarks). Two of the maps are so poor in information that it is obvious that little, if any, spatial knowledge exists. One of the remaining two maps, **Figure 4.8**, does not really fall into any of the three primary categories, as it compartmentalizes the environment into separate regions. The % RMS error of this map is around the overall average % RMS error at 62.3, but it cannot be considered to fall into any of the three primary categories of landmark, route, and survey. The final map in this category provides a more artistic interpretation of the environment (see **Figure 4.9**). This artistic 'personal narrative' of the space could be considered a qualitative form of sketch map; albeit one that bears little resemblance to a traditional map. While this map is interesting from a qualitative viewpoint, it does little to communicate the participant's level of spatial knowledge of the environment.

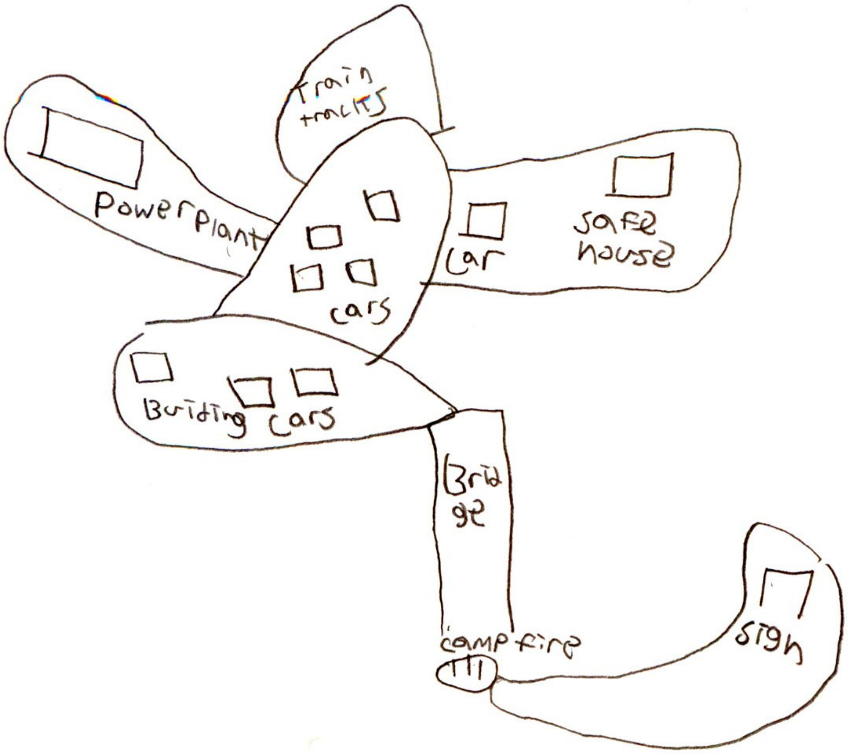


Figure 4.8 – An example of an 'other' category map. This map is not a route or survey map, but has an obvious hierarchical structure to the layout. The participant had partitioned the environment into distinct regions, although the metric knowledge is not of particularly high quality.

Figure 4.9 – Another example of an 'other' category map. This is a more artistic interpretation of the virtual environment. It is clearly not a map in the literal sense, but could be considered more of a visual narrative. This participant's RMS scores never improved beyond 550 despite changing to a more traditional map format for the second (landmark-type) and third (survey-type) sessions.

Pairing	W value	p-value	p-value adjusted for ties
Landmark x Route	56.0	0.7953	0.7953
Landmark x Survey	44.5	0.6892	0.6879
Route x Survey	391.0	0.9488	0.9488
Landmark x Other	13.5	0.2482	0.2482
Route x Other	243.0	0.0288**	0.0288**
Survey x Other	128.5	0.0357**	0.0357**

Table 4.2 – Mann-Whitney U Test results comparing the qualitative groupings. One asterisk indicates significance at the 0.10 level; two indicate significance at the 0.05 level.

Table 4.2 shows the results of the Mann-Whitney U tests comparing the percentage RMS error of the different qualitative groupings. The statistical analysis of the three primary categories revealed that none were significantly different from one another in terms of % RMS error at either the 0.10 or 0.05 level (90% or 95%). The only pairings that were significantly different from one another at the 0.05 level are those involving the ‘other’ category. Given the small sample size of the other category (four maps) and the high levels of error (three of four maps scored 550, the highest possible RMS error), this is neither surprising nor particularly enlightening. That the other primary categories are not significantly different from one another is also not surprising, since the RMS scores indicate that metric spatial knowledge exists in all three groupings of maps.

These statistical results support the hypothesis regarding tenet one of the continuous framework: no pure landmark or route knowledge was found, metric spatial information was included in all sketch maps. The level of metric accuracy of all three of the primary groupings of sketch maps submitted following a single exposure are statistically indistinguishable from one another, and while variance existed, all contained at least some amount of metrically-scaled spatial knowledge. While one map in each of the landmark and route categories came close to the dominant framework’s description (particularly the route map in **Figure 4.4**), they all still indicated a certain amount of metrically-scaled spatial knowledge beyond what the dominant theory posited should exist. As described by Montello (1998), it is difficult to reconcile the idea of non-metric cognitive space, given that perceptual space is clearly metric (pg. 147). While it is possible that an individual could memorize a series of landmarks presented outside of the context of metric space, it is difficult to imagine that same individual gaining that knowledge from environmental navigation while not gathering any metric spatial knowledge at all. In this context, the continuous framework better explains spatial microgenesis.

However, from a qualitative perspective, it is clear that landmark, route, and survey are still valuable descriptors of how people conceptualize and communicate spatial information. Since none of the participants were given instruction on how to draw their maps (only that they should include the eight main landmarks), the presence of maps that can clearly be considered landmark-, route-, or survey-type maps speaks strongly to these forms as being a part of our conceptualization of what maps are. Additionally, when looking at the Red Group's performance from the first to the last session (the focus of the exploration of tenet two) there was evidence that a progression from one type of map to another can occur after repeated exposures. **Figure 4.10** shows two maps from the same participant: in the first session the map is a route-type with a % RMS error of 52.95, and in the third the map is a survey-type with a % RMS Error of 30.84. Clearly this participant's sketch maps moved from one state to another while improving dramatically in quality. While this is evidence that individuals can transition from one conception of space to another while improving spatial accuracy as described by the dominant framework, this progression was not the norm. Most participants stuck with one type of sketch map throughout the three sessions. As the data from the Red and Yellow Groups in session one shows, all of the maps submitted had some metrically-scaled spatial knowledge, supporting the continuous framework. **Figure 4.10** would seem to indicate that while metric knowledge exists after an initial exposure, transition from one mode of spatial representation to another can exist, which matches the progression described by the dominant framework. It would seem that both theoretical frameworks have insight to offer when describing this component of spatial microgenesis.

This may also have implications for spatial education as well. Consider the ideas that spatial microgenesis was built on, such as the work of Piaget and Inhelder (1967) and Hart and Moore (1973), who were concerned with the development of spatial representation in children. Children's drawing abilities are described in developmental stages, which can be useful for assessing mental and physical development (Kellogg 1969). It is possible that the conceptions of space provided by the dominant framework are related to the development of spatial ability with landmark-type maps representing a lower level of spatial ability than route and survey maps. While no statistical significance was found between the map types, it is true that error rates were the lowest in survey-type maps, the most sophisticated of the three map categories. It may be possible to add conceptualization of mental maps to an ontology of spatial education such as the one provided by Golledge, Marsh, and Battersby (2007). These map conceptualizations could potentially be a valuable tool for assessing a student's spatial mental capabilities.

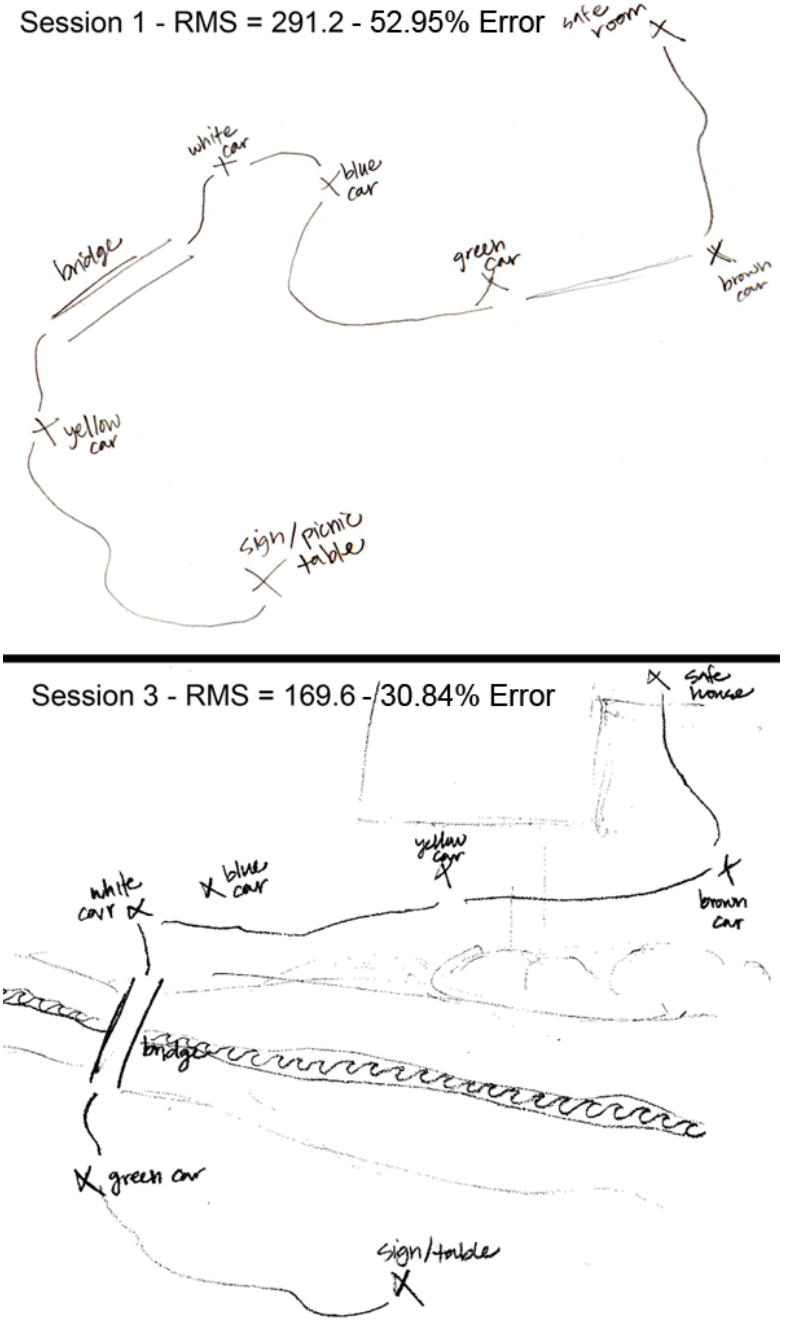


Figure 4.10 – An example of a sketch map in sessions one and three that improves in performance. Not only does the participant move from a route-type map to a survey-type map, RMS error improves by more than 120 points, nearly a 42% improvement in the error level.

Tenet Two – As experience grows with a place, so too does spatial knowledge

Both the dominant and continuous frameworks posit that knowledge of space will grow over time; the difference between the two is that the dominant framework suggests that this will occur in distinct, discrete stages. Regardless of the differences in how it happens, both frameworks say that with increased exposure to a place, spatial knowledge of that place should improve. To test the second tenet of the continuous framework, performance was compared between the first and final sessions for participants in the Red Group, who had no exposure to the map prior to the 10 minute exploration phase of the study sessions. If the continuous framework is correct in suggesting that knowledge grows over time, improvements should be seen from the first to final sessions. Direction, distance, and sketch map data were measured in total percentage error for each task (originally recorded in absolute degrees, centimeters, and RMS error respectively). Boxplots and graphs of mean error percentages showing the changes from session one to three can be seen in Figures **4.11-13**.

Looking at the direction task, the change in means can be seen graphically in **Figure 4.11**. Direction estimation improves from session one to three, although the decline in percent error is less than 1% (14.7% to 13.9%). The boxplots show that much of the change comes from reducing the number of high percentage error performers, and a tightening of the range of scores. A similar improvement is seen when evaluating change in error associated with the distance estimation task (**Figure 4.12)**. Performance improves from session one to three from 50.8% to 42.4% error, with a similar reduction in high error outliers.

In regards to the RMS error, we have yet again the same shift in **Figure 4.13**. Some participants progressed from one type of map to the next over the course of the sessions, such as the change seen in **Figure 4.10**, where the map moves from a route-type map to a survey-type map while also improving RMS error by more than 120 points, a nearly 42% performance increase. However, the majority of the participants drew roughly the same map in each session, with minor changes from one session to the next. Because of this, the change in mean performance is not very large, dropping from 66.7% to 62.7%.

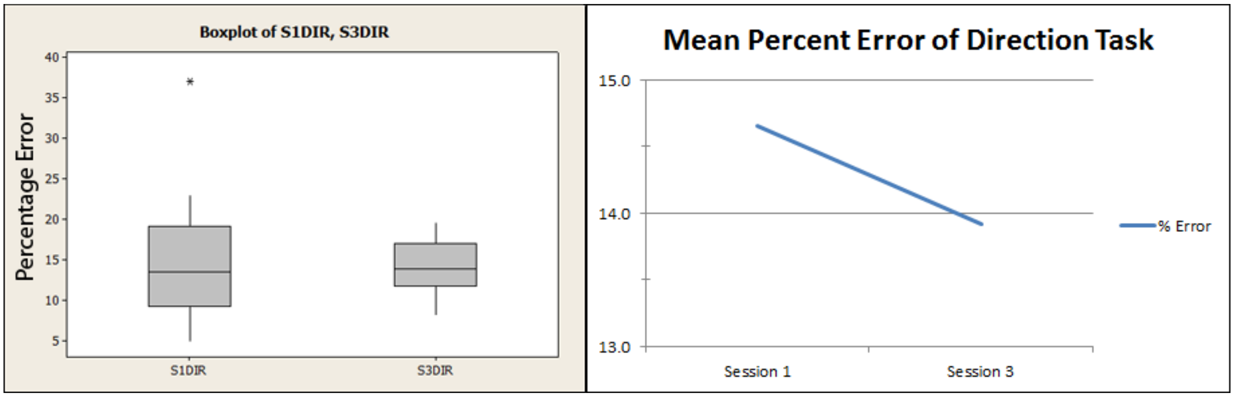


Figure 4.11 – Boxplot and graph of mean error in sessions one and three for the direction task.

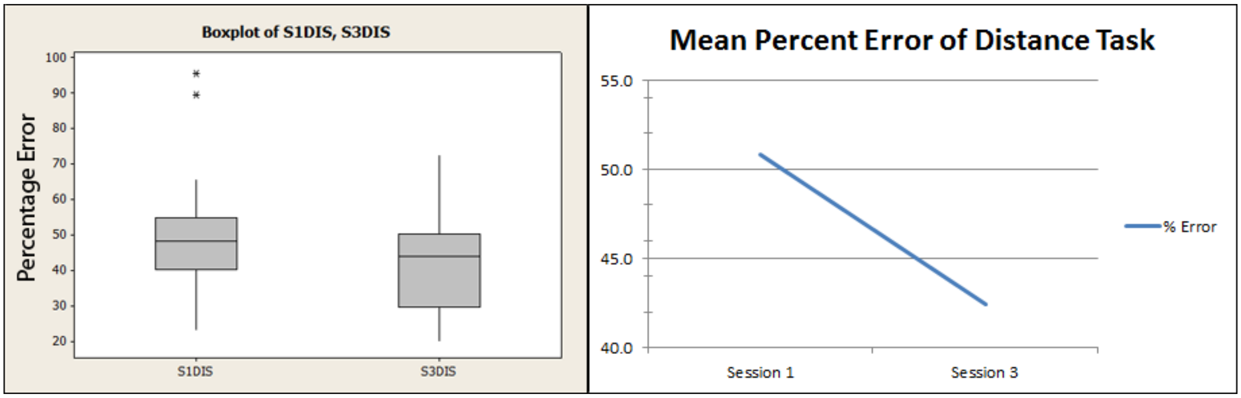


Figure 4.12 – Boxplot and graph of mean error in sessions one and three for the distance task.

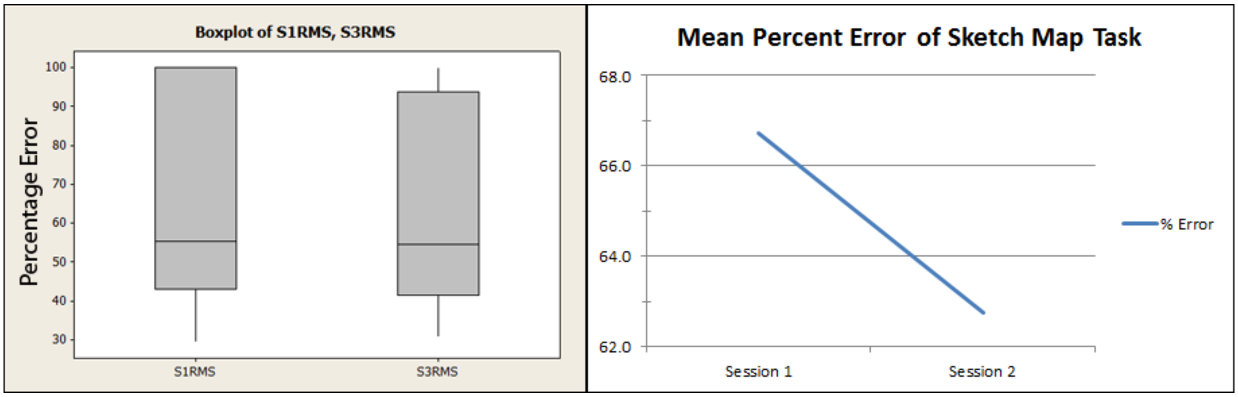


Figure 4.13 – Boxplot and graph of mean error in sessions one and three for the sketch map task.

Task	W value	p-value	p-value adjusted for ties
Direction	405.0	0.9031	0.9031
Distance	473.0	0.0909*	0.0909*
RMS	421.5	0.7660	0.7629

Table 4.3 – Mann-Whitney U Test results comparing first and last session performance for tasks. One asterisk indicates significance at the 0.10 level; two indicate significance at the 0.05 level.

The Mann-Whitney U results in **Table 4.3** indicate that the change in performance for both the direction and sketch map tasks are not significant, but the change in the distance task performance is significant at the 0.10 level (90%). Therefore, the hypothesis dealing with tenet two had mixed results. Error in spatial tasks decreased for all three tasks, but on only one task did this decrease reach a statistically significant level. Some individuals obviously improved their scores, since the boxplots in **Figures 4.11-13** show smaller ranges and fewer outliers in the third session, but on the whole performance didn't generally improve much excepting the distance task, which tends to be a more difficult task to complete (Gärling, Böök, and Ergezen 1981). This is consistent with previous findings, such as Ishikawa and Montello (2006) and Gärling, Böök, and Ergezen (1981), who found that beyond early sessions, performance did not generally improve much, even over the course of ten sessions across as many weeks. This study has a far shorter period of exposure than those studies, thirty minutes total over the course of three weeks, but the results appear to be quite similar. The only difference is the improvement in the distance task seen in the current study, but given that distance estimation tends to be more difficult to complete than direction estimation, it would make sense that participants had more room for improvement over the course of the sessions. It is possible that improvements in performance might have become more dramatic had the study run longer, but the results of Ishikawa and Montello and Gärling, Böök, and Ergezen suggest that it would need to be quite a long time indeed if this improvement were to appear in the data.

The continuous framework does not say that spatial microgenesis will occur in the absence of attention: "it is likely that people do not acquire much metric knowledge without paying attention to the environment and/or to their movement" (Montello 1998 pg. 148). However, given that participants in this study were asked to pay attention to the environment and remember the locations of landmarks, it is problematic that the improvements in spatial knowledge over time are small and that only one category of tasks shows a statistically significant improvement. These results, as well as those of Ishikawa and Montello (2006) and Gärling, Böök, and Ergezen (1981), suggest that repeated exposure to an environment alone may not be enough to lead to improvements in spatial knowledge.

In the real world, day-to-day navigation can have serious consequences in an individual's life, so reaching a competent level of accuracy and ability in collecting spatial knowledge is intrinsically encouraged, whereas within the confines of this research, there were no consequences or rewards for performance. Feedback about the quality of participants' performance was not provided from session to session, which may have removed a potential avenue towards learning. Essentially, participants were given no motivation to try harder, and whether they believed their work to be of a high quality or not, they had no way of knowing for sure. This may have left them less inclined to attempt to improve performance in later sessions.

Overall performance did improve as evidenced by the results in **Figures 4.11-13**, although it was not a major shift in error rates. It is possible that the drop in error might have been more dramatic (and had a higher level of statistical significance) had participants been given feedback or rewards for their task performance, or been asked to use specific strategies for learning spatial knowledge. Some possible strategies for improving performance have been discussed by Cornell, Heth, and Rowat (1992) and Thorndyke and Stasz (1980). Cornell, Heth, and Rowat describe a look-back technique where individuals regularly turn to face the route they have walked as they navigate. This provides more context to the locations of landmarks and improves the chances of successful navigation. Thorndyke and Stasz discuss techniques related to knowledge gained from map reading, including partitioning the map into regions (although these map techniques would not apply directly to the Red Group, as they received no exposure to the official map).

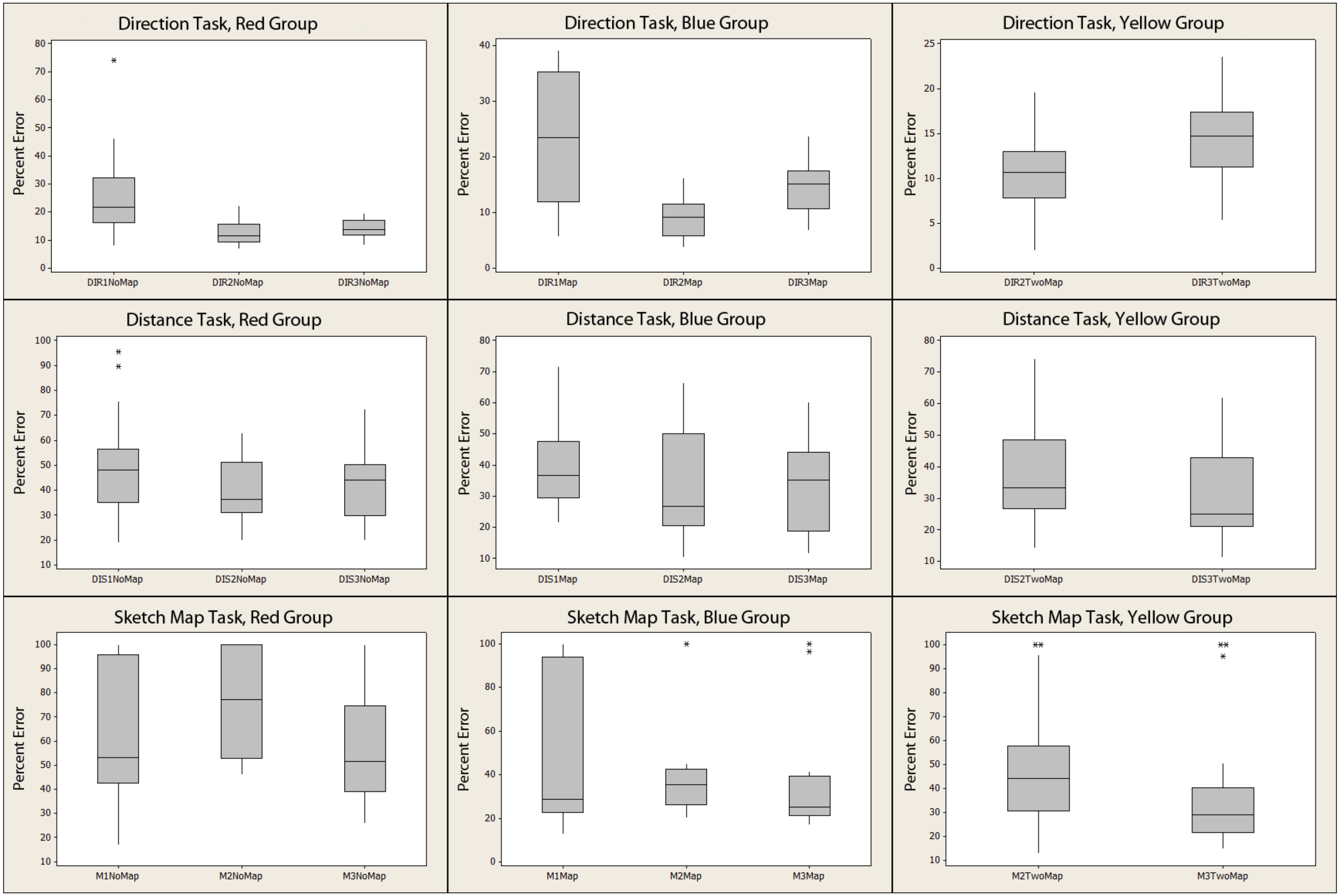
Tenet Four – Individuals with similar amounts of exposure to a place will differ in the extent and accuracy of their spatial knowledge

The fourth tenet looks at within-group variation of participant performance. If tenet four of the continuous framework is correct, groups who shared similar exposure to the environment will have variation in their error rates. To test this, the data was divided into twenty-four groupings based on the task, session, and amount of map exposure. The descriptive statistics about each group/task/session combination can be seen in **Table 4.4**, and boxplots of group performance are found in **Figure 4.14**. A histogram of the coefficient of variation (CV) scores is in **Figure 4.15**.

Participants did all three tasks in all three sessions while either viewing the map or not viewing the map of the environment, but since the Yellow Group were exposed to the map only in sessions two and three, there are only twenty-four groupings instead of only twenty-seven. Looking at the CV scores, we can see that it varies from treatment to treatment, the lowest value being 24 in the Red Group third session direction task, and the highest being 74 in the Blue Group third session sketch map task. A histogram showing the breakdown of the CV scores can be seen in **Figure 4.15**. Note that while the overall distribution is normal, three of the CV scores are much higher and cluster to the right of the chart. Seeing these CV scores for performance on spatial tasks is useful, as there is no set threshold for what qualifies the CV as 'high' or 'low' in the realm of spatial microgenesis. Given that variation in a measurement is specific to the domain which is being measured, it is not applicable to look to other fields for levels of 'acceptable' variation. The example provided in the Introduction chapter was a hypothetical manufacturing plant vs. a classroom. The upper threshold for what is considered acceptable variation in the production of a consumer good might be as low as 0.5. Whereas in the context of a classroom, it is understood that performance will vary between students, and what counts as an acceptable CV of performance might be much higher. Within this research dataset, the lower bound of variation in individual performance is 24, and the upper bound is 74. This one study cannot be the sole decider of what is deemed a high or low CV in spatial performance, but it is hoped that these numbers can provide a context for future work.

Red Group								
Task	**N**	**Mean**	**Std. Err.**	**StDev**	**Variance**	**CoefVar**	**Minimum**	**Maximum**
Direction S1	45.0	24.9	1.9	12.7	161.5	51.1	8.0	74.2
Direction S2	20.0	13.2	1.0	4.6	20.7	34.6	7.0	22.4
Direction S3	20.0	13.9	0.7	3.3	11.2	24.0	8.2	19.6
Distance S1	45.0	48.1	2.5	16.8	281.2	34.9	19.0	95.6
Distance S2	20.0	39.9	2.8	12.6	159.1	31.6	19.8	62.9
Distance S3	20.0	42.4	3.1	13.7	188.1	32.3	20.0	72.6
Sketch Map S1	45.0	61.9	4.0	26.8	716.5	43.3	16.9	100.0
Sketch Map S2	20.0	76.1	5.0	22.2	491.0	29.1	46.1	100.0
Sketch Map S3	20.0	59.0	5.6	24.8	616.5	42.1	26.0	100.0
Blue Group								
Task	**N**	**Mean**	**Std. Err.**	**StDev**	**Variance**	**CoefVar**	**Minimum**	**Maximum**
Direction S1	13.0	24.0	3.2	11.6	135.2	48.5	5.7	39.1
Direction S2	13.0	9.2	1.1	3.8	14.4	41.3	3.7	16.2
Direction S3	13.0	14.5	1.4	5.0	25.3	34.6	6.9	23.7
Distance S1	13.0	39.3	4.0	14.3	203.4	36.3	21.6	71.8
Distance S2	13.0	34.1	5.0	18.0	322.1	52.7	10.4	66.6
Distance S3	13.0	32.8	4.1	14.9	222.1	45.5	11.7	60.2
Sketch Map S1	13.0	48.3	9.7	34.9	1214.3	72.1	12.7	100.0
Sketch Map S2	13.0	38.1	5.7	20.4	414.5	53.4	20.2	100.0
Sketch Map S3	13.0	37.6	7.7	27.8	774.8	74.0	17.0	100.0
Yellow Group								
Task	**N**	**Mean**	**Std. Err.**	**StDev**	**Variance**	**CoefVar**	**Minimum**	**Maximum**
Direction S2	25.0	10.6	0.9	4.3	18.4	40.5	1.9	19.6
Direction S3	25.0	13.8	1.0	4.8	22.8	34.5	5.4	23.7
Distance S2	25.0	38.1	3.4	16.8	281.0	44.0	14.3	74.2
Distance S3	25.0	31.2	2.8	14.1	198.3	45.1	11.4	61.9
Sketch Map S2	25.0	48.6	4.9	24.3	588.8	49.9	13.1	100.0
Sketch Map S3	25.0	36.5	5.0	25.1	629.5	68.7	14.9	100.0

Table 4.4 – Descriptive statistics of group performance including the coefficient of variation.



Direction Task, Red Group

Direction Task, Blue Group

Direction Task, Yellow Group

Distance Task, Red Group

Distance Task, Blue Group

Distance Task, Yellow Group

Sketch Map Task, Red Group

Sketch Map Task, Blue Group

Sketch Map Task, Yellow Group

Figure 4.14 – Boxplots showing the within-group performance for each task/session/map exposure combination. In session one, the Red and Yellow groups are combined since they had the same experience (first session, no map exposure).

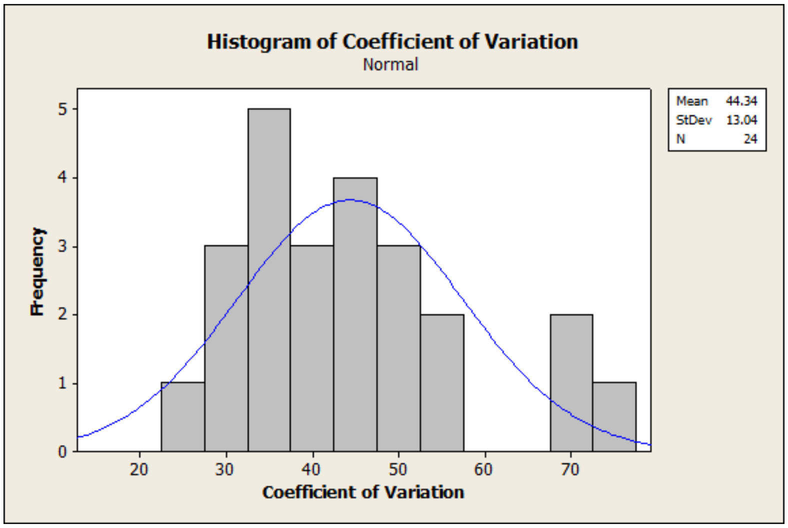


Figure 4.15 – Histogram showing the distribution of coefficient of variation scores.

The coefficient of variation says nothing about the overall quality of the results, it only describes the range of scores. Comparing the mean error scores of the direction task in the third session between the Red and Yellow Groups, the means are nearly identical at 13.9% and 13.8% respectively. Yet the CV scores for these two groups are 24 and 34.5 respectively. Per the fourth tenet, we are concerned primarily with the range of scores indicated by the CV, not the mean error rates. If the tenet is correct, each grouping of individuals with similar levels of exposure to the environment should still contain variation in the amount of error. While some of the CV scores are much lower than others, it is safe to say that even in these low CV groups variation still exists in individual performance, albeit much less than exists in some of the high CV groups. It is worth noting that the highest CV values are found in sketch map related treatments, and not in the Red Group. This suggests that in the absence of the assistance that map exposure provides, individuals performed similarly poorly, but that map exposure may have had differing effects on individuals. Some participants were able to take better advantage of the map exposure than others.

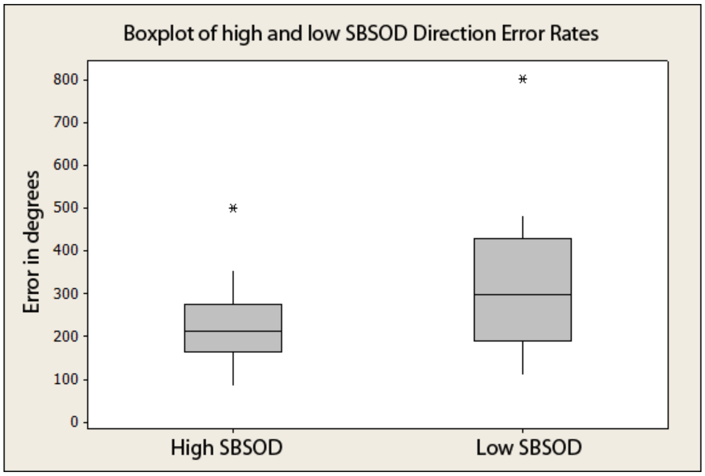


Figure 4.16 – Boxplot showing error in degrees for high and low SBSOD participants for the direction task.

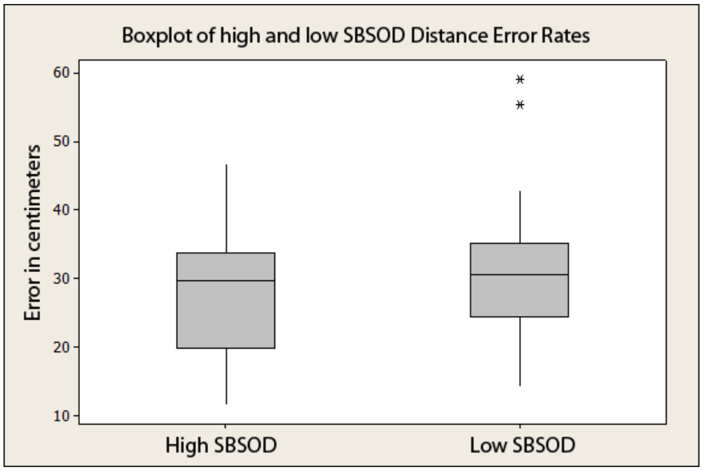


Figure 4.17 – Boxplot showing error in centimeters for high and low SBSOD participants for the distance task.

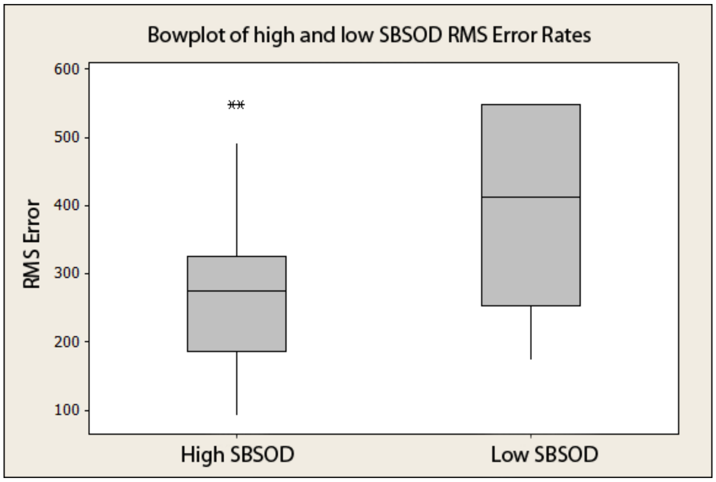


Figure 4.18 – Boxplot showing RMS error for high and low SBSOD participants for the sketch map task.

Task	W value	p-value	p-value adjusted for ties
Direction	427.0	0.0212**	0.0212**
Distance	498.5	0.4958	0.4987
Sketch Map	425.0	0.0188**	0.0179**

Table 4.5 – Mann-Whitney U Test results comparing performance on tasks between those with high and low SBSOD scores in the Red Group. One asterisk indicates significance at the 0.10 level; two indicate significance at the 0.05 level.

Task	N	Mean	Std. Err.	StDev	Variance	CoefVar	Minimum	Maximum
High SBSOD Scores								
Direction	23	20.55	1.83	8.80	77.44	42.83	7.96	46.20
Distance	23	45.82	3.19	15.28	233.44	33.34	18.96	75.69
Sketch Map	23	51.55	4.69	22.51	506.83	43.67	16.87	100.00
Low SBSOD Scores								
Direction	22	29.39	3.13	14.67	215.30	49.92	10.19	74.17
Distance	22	50.50	3.89	18.24	332.83	36.15	23.10	95.62
Sketch Map	22	72.63	5.77	27.06	732.40	37.26	31.71	100.00

Table 4.6 – Descriptive statistics of performance of those with high and low SBSOD scores.

In an attempt to explain the variance found in the groups, the largest group with similar exposure to the environment was analyzed more closely. The results of the 45 participants who did not see the official map in the first session were broken down into two categories, those with high SBSOD scores, and those with low scores. The SBSOD scores in this group ranged from 43 to 95, and the median score of 73 was used to divide the participants. This created a group of 23 who scored 73 or higher, and one of 22 who scored below 73 on the SBSOD survey. The statistical results of the Mann-Whitney U test as seen in **Table 4.5** showed that the two groups' performance was significantly different at the 0.05 (95%) level for the direction and sketch map tasks, while the distance task was not significantly different. Boxplots of the data can be seen in **Figures 4.16-18**, and descriptive statistics of the two groups can be seen in **Table 4.6**. The statistical difference between the groups is not surprising, as those who report having better spatial skills would be expected to out-perform those with poorer skills. That the distance task is not significantly different is more interesting, but explained again by the fact that it tends to be a more difficult task to complete in general (Gärling, Böök, and Ergezen 1981). However, when the descriptive statistics are viewed, things become less clear. The high SBSOD group has less variance in performance on the direction and distance tasks, but when it comes to the sketch map task (where the difference between the high and low groups had the greatest statistical significance), the high SBSOD group actually has a higher level of variance. It is intuitive that the high SBSOD scores would lead to better performance, but evidently this performance increase does not necessarily translate to less variance within the group.

The hypothesis dealing with tenet four, that variation will be found in all groupings, is proven correct. The continuous framework of spatial microgenesis correctly predicts that individual performance will vary from one person to another. This is not a particularly surprising result, given that anecdotally we all know individuals who are extremely good completing at everyday spatial tasks, as well as those who are extremely poor at the same tasks. The continuous framework does not make an attempt to explain these differences beyond stating that "….individuals will also differ in both fundamental abilities for acquiring spatial knowledge (intellectual abilities) and in acquired strategies for encoding and decoding spatial knowledge (which should be amenable to training)" (Montello 1998, pg. 149). This is an area which deserves further examination, as both this research and Ishikawa and Montello (1998) find the variation from one individual to another to be an important unexamined element of spatial microgenesis. Specifically, Ishikawa and Montello (2006) had this to say: "So even though the continuous framework stresses the importance of large individual variations, it still does not do full justice to the significant qualitative as well as quantitative nature of the variations" (pg. 122).

While it is likely that biology plays a role in spatial ability, it is possible that the gap between good and poor performers might become smaller following education in spatial thought. Recalling the discussion of geospatial education in the literature review chapter, there is evidence that training in childhood could improve spatial abilities in general, potentially reducing some of the variation in ability seen from one individual to the next (Gregg 1999; Uttal 2000). Given that the survey results revealed that many students enrolled in intro-level geography classes had had little to no formal training in regards to the realm of spatial thought, it is possible that large gains in performance could be seen if students were exposed to spatial concepts at a younger age. Training individuals to improve their spatial microgenesis abilities (also discussed in regards to tenet two) could have benefits to society in the form of improved STEM outcomes in education as well as the immeasurable improvements to our day-to-day lives, and would be hard to argue against.

Results Summary

The dissertation focuses on the question of which theoretical framework, the continuous or dominant, does a better job of describing the process of spatial microgenesis. To do so, three of the five tenets of the continuous framework were tested for validity. The first tenet states that no stage of pure landmark or route knowledge exists, but rather that metrically-scaled survey knowledge will exist from the first exposure to an environment. To test this, sketch maps provided by the two experimental groups with no exposure to the official map prior to exploring the virtual environment were qualitatively categorized into landmark, route, survey, and other categories. Statistical analysis of the RMS error from georeferenced sketch maps showed that there were no differences in the scores for each of the primary categories, proving correct the hypothesis that there was no pure landmark or route knowledge in the maps. Despite this, sketch maps were easily categorized using qualitative methods as landmark-, route-, or survey-type maps. Within the landmark and route categories, maps existed that closely resembled the descriptions of landmark and route knowledge provided by the dominant framework while still containing a small amount of metric knowledge. While the continuous framework is correct in positing that survey knowledge exists from first exposure, the descriptions of knowledge from the dominant framework are clearly important to how people conceptualize knowledge of space. These conceptualizations may also be a useful rubric for assessing the growth of spatial ability in children as a part of a larger spatial task ontology.

The second tenet states that knowledge of space will grow over time and the hypothesis related to this tenet states that error in spatial tasks will significantly decrease after repeated exposure to place. Experimental results, however, were mixed. Looking at results from the Red group, who did not view the official map at any point, there was improvement in the performance of all three tasks, but the improvement associated with only one (the distance task) was a statistically significant at the 90% confidence level. It is possible that additional improvement may have been found had the sessions gone for a longer period of time, but literature suggests that beyond the first few exposures, improvement is not likely to be seen. It is also possible that a lack of motivation to improve performance may have played a role in the relatively small improvement measured. Given more feedback and encouragement, the experimental group may have had significant improvement in the tasks beyond just the distance task. These results are in agreement with prior literature on the subject.

The fourth tenet states that given similar levels of exposure, variation will exist in performance, the hypothesis being that variation in scores will exist in all groupings of similar experience. Proving the hypothesis correct, each of the 24 groupings of participants showed variation in performance, with coefficient of variation scores ranging from 24 to 74. The SBSOD scores of participants were examined as a potential explanation for some of the variance, but this analysis did not provide a clear explanation. Given that CV is highly dependent on the domain in which it is being measured, the scores collected for this research will help to create a baseline of variation in performance on spatial tasks that can be used by future work, as variation in performance remains a poorly explained component of spatial microgenesis.

Chapter 5 - Discussion and Conclusions

The dominant framework has been influential to how we think of spatial microgenesis, having been cited over one thousand times according to the Google Scholar search engine (Google 2012). Clearly, this theoretical framework has informed the thinking of a great number of researchers. Montello's continuous framework attempts to update the dominant framework, but it is still more of an outline of what may happen for those with good spatial abilities, rather than a description of the process that applies to everyone (Ishikawa and Montello 2006). This dissertation addressed the lack of independent research that directly compares the two frameworks. Toru Ishikawa's dissertation (2002) is one of the few studies addressing the issue, and added support for the continuous framework of spatial microgenesis, especially with regards to the third tenet. However, he found very little improvement in spatial abilities in most individuals during the course of a ten week study. This was problematic for tenet two of the continuous framework, which states that given more exposure, the amount and quality of spatial information should increase in an individual. In this dissertation, the two theoretical frameworks were compared by exposing participants to a novel environment, then testing their spatial knowledge. If the dominant framework correctly describes spatial microgenesis, the participants' spatial knowledge would progress over time through the three distinct stages it describes. If the continuous framework is correct, gaining spatial knowledge would be better described by the five tenets.

Three of the five tenets were examined in this research, the first, second and fourth. The first tenet states that there is no stage of pure landmark or route knowledge, but rather that metrically-scaled survey-type knowledge exists from an initial exposure. For testing this tenet, the hypothesis was that no pure landmark or route knowledge would exist after an initial exposure to a novel environment. What was found is that all of the maps created by participants showed evidence of metrically-scaled spatial knowledge of the environment. That being said, the old stages of knowledge from the dominant framework remain important, as the majority of the maps could be easily categorized using qualitative methods as landmark-, route-, or survey-type maps. Comparing the means of error between the categories, there was no statistically significant difference in the metric quality of the maps, indicating that they are not representing stages of knowledge the way the dominant framework describes them. However, these categories clearly help to describe how individuals conceptualize their spatial knowledge.

The second tenet says that spatial knowledge will grow over time. The hypothesis for this tenet was that error in spatial tasks would significantly decrease after repeated exposures to an environment. These results were mixed, as error on all three tasks decreased, but statistically significant improvement was measured for only one of the three tasks, distance estimation. Distance estimation is considered the most difficult of the tasks, so it is possible that participants simply had more room to improve when compared to the other tasks (Gärling, Böök, and Ergezen 1981). These results match those of Ishikawa and Montello (2006), who found that many participants did not significantly improve in their ability to perform spatial tasks over time. This is a troubling result for both the dominant and continuous frameworks, since both posit that knowledge should be increasing with more exposure. In light of the lack of overall improvement, Ishikawa and Montello come to the conclusion that the continuous framework is a description of how spatial microgenesis works for those with good spatial abilities, and that while it addresses individual differences with the fourth tenet, it does not go far enough in dealing with the disparity in performances from one individual to another. It is possible that increasing the amount of exposure to the novel environment may lead to greater improvements, but both Ishikawa and Montello (2006) and Gärling, Böök, and Ergezen (1981) found that beyond initial exposures, most individuals failed to show any great improvement. What may be more important to gaining spatial knowledge than exposure time is incentive and feedback to learning. This is one avenue for future research on the subject, to see how individuals respond to feedback and incentives to learning spatial information. In the real world, successful recall of space has very practical implications in regards to navigation; in this study, there was no feedback about the quality of performance. Also, considering the limitations of virtual environments, it is possible that reproducing this study in a real-world environment would change the results. Considering that the outcomes here were broadly in line with those of Ishikawa and Montello (2006) and Schinazi *et al.* (2009), it seems unlikely that there would be any dramatic changes in the results, but it is possible that the outcomes would be different. Especially in light of the limitations that virtual environments put on peripheral vision and proprioceptive information, reproducing the study in the real world could lead to generally lower error rates across the board.

The fourth tenet posits that given similar levels of exposure to place, individuals will have different amounts of spatial knowledge. The hypothesis related to this tenet was that all groupings of individuals with similar exposure would show variation in their performance on spatial tasks. As expected, the hypothesis and the continuous framework were shown to be correct: variance in performance existed in all groupings of participants with similar levels of exposure to place. What was unexpected was the range of variance from one grouping to another. The lowest coefficient of variance (CV) score was 24, and the highest was 74. Some of the highest CV scores came from the Blue group, who were exposed to the map prior to every session. In many cases, the Red group who had no map exposure had a lower CV while having a higher mean error rate. This may indicate that the participants in the Red group did similarly poorly, but that exposure to maps may not improve all participants' scores. It is possible that some participants were better able to take advantage of the map exposure than others. Some research has already shown that map exposure helps the spatial microgenesis processes (Thorndyke and Hayes-Roth 1982), while Moeser (1988) found that without map exposure, no survey-type knowledge is generated at all.

Additionally, a closer look at the SBSOD scores of participants did not provide much insight to the levels of variation. On direction and sketch map tasks, participants with higher SBSOD scores performed significantly better than those with low scores. Yet the high score group managed to have a higher level of variance on the sketch map task than the low score group. It was expected that the high score group would have lower error rates, but not that their coefficient of variation scores would be higher than the low score group. Specifically relating to the fourth tenet, avenues for potential future work include exploring the impact that map exposure has on the spatial microgenesis process, as well as the factors that may be affecting differences in individual performance, such as education in spatial thought.

This dissertation largely supports the continuous framework over the dominant, in that it found no evidence that pure landmark or route knowledge exists after an initial exposure. In fact, most participants had far more spatial knowledge than they should have according to the dominant framework. However, as mentioned before, the dominant framework should not be dismissed entirely, since the concepts of landmark, route, and survey knowledge were on display in the maps that were drawn by participants. The widespread influence of the dominant framework may in part be why these conceptions of maps persist, but regardless, they are an element of individuals' understanding of maps.

Despite being a better description, the continuous framework is still not a complete view of how spatial microgenesis occurs. In general, little improvement was seen from the first to last session, with the exception of the distance estimation task. Also, given the outcomes of Ishikawa and Montello (2006) and Gärling, Böök, and Ergezen (1981), one can assume that further improvements would not likely be statistically significant. The other major problem faced by the continuous framework is the huge disparity in ability from one individual to the next. The continuous framework acknowledges these differences in tenet four, stating that "Individuals with equal levels of exposure to a place will differ in the extent and accuracy of their spatial knowledge" (Montello 1998 pg. 147). This is a bit of an understatement given the huge coefficient of variation scores and the large range of SBSOD scores, going from 43 to 95 on the 15-105 point scale. These differences are a problem for the continuous framework, given that it is supposed to provide an outline of how the process works for an average individual. Some of the participants in this research had shockingly low rates of error on spatial tasks after the first exposure, while others seemed incapable of recalling much, if any, spatial knowledge. The nature of these differences in ability is unknown, although it is safe to say that there are likely elements of both nature and nurture playing a role. Most of the participants in this study had little formal education in spatial thought, even when the students from the GIS course are included. It is possible that education in spatial geographic concepts could improve outcomes in ability, and is one avenue for future research. For example, a follow-up study could look at performance of students both before and after taking part in geospatial courses to see if the courses had any impact on spatial abilities. Of course, like many questions of nature vs. nurture, a long-term longitudinal study would be ideal, if impractical. Since it has been shown that young children can learn complex spatial concepts and both retain and build on that knowledge as they grow (see literature review for the longer discussion), being able to track spatial abilities from a young age through adulthood while also tracking geographic spatial education would help to answer this question.

The continuous framework rejects the central premise of the dominant framework (that knowledge grows through three distinct phases), but one of this study's largest findings is that the landmark, route, and survey knowledge are an important descriptor of individuals' spatial knowledge. While they clearly do not represent stages of knowledge gathering, landmark, route, and survey are valuable descriptors of how individuals conceptualize mental maps. And although the maps that were classified as survey maps were not significantly better in terms of RMS error, they did have a lower mean error score, as well as including far more detail and context to the mapped environment. This level of quality is desirable, as it may indicate that individuals are better equipped to deal with spatial tasks. In light of the spatial education discussion in the literature review, this could possibly point to an additional rubric in the educational system for measuring students' spatial abilities. This rubric of map conceptualization could be added to a spatial task ontology, such as the one presented by Golledge, Marsh, and Battersby (2007), which would help to ensure that students receive the assistance they need to be able to effectively think spatially.

Beyond commenting on the dominant and continuous frameworks of spatial microgenesis, several notable results came from this research. One is the use of ArcGIS's RMS error values as an objective quantitative measurement of metric sketch map quality. While some past studies have employed qualitative measures of map quality (Billinghurst and Weghorst 1995), and others bidimensional regression for quantitative measurements (Ishikawa 2002), this study employed the ArcMap software's georeferencing capability. This tool provides a simple point and click interface to transform raster data to better fit the spatial realities of the Earth's surface. Its intention is to convert imagery to a correctly projected state, but as a part of that process, it provides an error measure to indicate the quality of the initial image in relation to the transformed one. In the context of sketch map analysis, it is believed that this is a novel approach to measuring map error quantitatively, and could easily be employed by anyone with access to ArcGIS software.

Another useful contribution is the coefficient of variation scores that were generated from the research participants' data. Since what constitutes a high or low coefficient of variation in a sample is heavily dependent on the domain being explored, having these values available provides a baseline for future research into spatial microgenesis. The scores varied quite a bit, and this has provided some insight into the nature of spatial microgenesis, as well as the potential impacts that map exposure and geographic education may play in the process. This research also provided a snapshot of the level of geographic education among undergrad students enrolled in introductory geography courses. What it found is that the vast majority of students had never received any formal training in geographic activities such as map and compass reading. This may help explain the United States' lagging performance in the STEM fields, as spatial thinking is a crucial component of these fields.

While this dissertation does not conclusively answer the question of how spatial microgenesis works, it does help to shed some light on Montello's continuous theoretical framework. The continuous framework is a more complete description of spatial microgenesis than the dominant framework, but it still falls short, particularly in describing the growth of knowledge over time and the individual differences in spatial performance. Additionally, the concepts of landmark, route, and survey knowledge provided by the dominant framework remain important to our conceptualizations of space. Some of the larger unanswered questions deal with the role of incentives in spatial learning, and the role that education in geographic thought may have on the spatial microgenesis processes. Improvements in geographic education could have widespread benefits, including improved performance in the STEM fields, and more efficient day-to-day spatial experiences. It is hoped that this dissertation has helped to clarify elements of the two major theoretical frameworks that describe spatial microgenesis, and provoked some thought for future explorations of the topic.

Chapter 6 - References

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Appendix A - Santa Barbara Sense of Direction Survey

Name:________________
Today's Date:________________
Age:_______

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

1. I am very good at giving directions.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
2. I have a poor memory for where I left things.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
3. I am very good at judging distances.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
4. My "sense of direction" is very good.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).
   strongly agree 1 2 3 4 5 6 7 strongly disagree
6. I very easily get lost in a new city.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
7. I enjoy reading maps.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
8. I have trouble understanding directions.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
9. I am very good at reading maps.
   strongly agree 1 2 3 4 5 6 7 strongly disagree
10. I don't remember routes very well while riding as a passenger in a car.
    strongly agree 1 2 3 4 5 6 7 strongly disagree
11. I don't enjoy giving directions.
    strongly agree 1 2 3 4 5 6 7 strongly disagree
12. It's not important to me to know where I am.
    strongly agree 1 2 3 4 5 6 7 strongly disagree
13. I usually let someone else do the navigational planning for long trips.
    strongly agree 1 2 3 4 5 6 7 strongly disagree
14. I can usually remember a new route after I have traveled it only once.
    strongly agree 1 2 3 4 5 6 7 strongly disagree
15. I don't have a very good "mental map" of my environment.
    strongly agree 1 2 3 4 5 6 7 strongly disagree

Santa Barbara Sense of Direction Survey Results

	Questions														
Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTAL
1	7	3	6	5	3	4	4	6	2	6	7	6	6	2	6	73
2	3	5	5	2	3	3	1	5	4	3	2	7	1	1	6	51
3	5	6	5	5	3	6	4	6	6	5	4	5	5	5	4	74
4	5	5	5	4	3	2	5	3	4	2	3	1	3	5	3	53
5	3	5	2	3	3	6	6	5	5	4	5	5	5	3	3	63
6	6	7	6	5	7	4	3	5	5	6	4	7	7	6	6	84
7	4	6	4	3	7	5	5	6	5	5	5	6	4	2	5	72
8	5	4	6	6	3	4	5	6	6	6	4	6	4	6	6	77
9	5	4	4	5	3	6	6	5	6	3	4	5	6	5	5	72
10	5	5	4	5	4	5	3	5	5	5	4	7	4	4	5	70
11	4	2	5	5	5	1	5	4	5	1	1	3	1	5	1	48
12	7	3	5	5	3	4	5	5	5	5	3	5	4	5	5	69
13	1	4	2	2	6	7	6	6	3	1	4	6	2	3	5	58
14	6	5	5	6	1	7	1	7	7	4	5	7	6	6	5	78
15	5	6	5	4	2	5	5	6	6	6	4	6	6	5	5	76
16	3	6	2	5	2	3	2	3	3	6	2	6	2	6	5	56
17	6	5	7	4	3	5	7	5	7	5	5	5	4	4	5	77
18	5	2	5	5	3	4	3	4	5	4	4	4	4	4	3	59
19	5	4	4	3	2	5	4	4	3	3	5	6	3	3	5	59
20	3	6	4	3	1	6	1	5	1	3	3	4	5	3	4	52
21	4	3	6	5	3	3	5	4	7	1	2	2	2	4	3	54
22	6	6	7	5	1	5	6	2	2	5	5	7	6	7	6	76
23	6	6	5	5	4	2	3	6	5	4	4	6	2	3	4	65
24	5	5	6	6	5	6	6	5	6	6	4	7	5	7	5	84
25	7	2	6	7	6	6	4	6	5	6	5	1	4	7	7	79
26	5	6	7	6	2	5	6	7	6	7	4	7	7	7	7	89
27	3	5	2	2	1	5	3	5	3	2	2	3	2	3	3	44
28	6	7	6	7	5	6	7	7	6	4	4	3	4	3	5	80
29	5	5	3	5	5	6	6	6	5	7	5	6	7	5	6	82
30	6	1	5	7	7	3	7	2	6	5	3	3	3	7	5	70
31	6	2	5	7	5	4	6	4	5	4	4	5	4	5	4	70
32	5	5	6	6	6	3	7	6	7	5	5	7	7	2	5	82
33	5	6	4	3	5	6	5	6	5	5	6	5	5	5	5	76
34	7	6	5	5	5	6	5	6	5	5	5	5	5	5	6	81
35	5	5	5	6	3	4	4	5	6	5	4	5	4	5	5	71
36	5	4	6	7	1	4	3	5	4	3	6	7	1	4	6	66
37	6	3	5	6	7	5	7	5	6	5	5	5	5	6	5	81
38	6	6	5	6	2	6	7	6	7	5	6	7	6	6	6	87

	Questions															
Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTAL
39	5	5	4	3	1	2	7	5	7	3	5	6	6	3	4	66
40	5	2	2	2	2	6	3	2	6	1	3	2	2	2	3	43
41	6	5	4	6	7	5	7	5	6	5	7	7	6	5	5	86
42	6	5	4	5	3	3	4	5	6	3	4	4	5	3	4	64
43	6	4	3	5	3	6	6	6	6	5	5	7	6	6	5	79
44	5	4	4	4	3	4	5	5	5	5	5	5	5	5	5	69
45	6	5	5	6	6	3	7	5	7	6	5	7	6	5	6	85
46	7	7	7	7	4	7	5	7	7	7	7	1	7	7	7	94
47	7	3	5	6	7	6	7	7	7	7	6	7	7	5	7	94
48	6	3	7	5	6	5	5	5	5	3	5	5	7	5	5	77
49	3	6	3	5	5	4	3	6	5	2	3	6	2	5	6	64
50	4	3	1	6	5	5	5	5	4	4	4	5	5	4	4	64
51	6	5	6	5	6	4	6	6	5	3	5	7	5	5	4	78
52	5	3	5	5	5	4	6	3	5	2	5	6	6	6	4	70
53	5	5	4	3	5	2	7	6	7	3	3	7	6	6	5	74
54	7	6	6	6	7	4	7	6	7	3	6	7	7	6	7	92
55	5	6	6	5	6	4	7	6	7	6	6	6	5	6	5	86
56	5	4	1	3	4	7	6	5	3	5	7	7	1	3	4	65
57	6	6	6	7	7	6	5	7	7	7	5	7	6	6	7	95
58	7	4	7	7	7	4	4	7	5	6	4	3	3	6	6	80

Survey of Spatial Education

Name:_________________
Today's Date:________________
Age:_______

This questionnaire consists of several questions about your spatial and navigational abilities, preferences, and experiences. After each statement, answer yes, no, or not sure.

1. I have received training in map reading and navigation skills.
    a. Yes
    b. No
2. If you answered yes to question one, where did you receive this training?
    a. Military
    b. School
    c. Boy Scouts
    d. Other (Please explain) ________________
    e. Answered no to question one
3. Have you received training in navigational skills such as the use of a compass?
    a. Yes
    b. No
4. If you answered yes to question three, where did you receive this training?
    a. Military
    b. School
    c. Boy Scouts
    d. Other (Please explain) ________________
    e. Answered no to question three
5. Have you received training in the use of Global Positioning System (GPS) devices?
    a. Yes
    b. No
6. If you answered yes to question five, where did you receive this training?
    a. Military
    b. School
    c. Boy Scouts
    d. Other (Please explain) ________________
    e. Answered no to question five
7. I have had training in the use of Geographic Information Systems (GIS).
    a. Yes
    b. No
8. If you answered yes to question three, where did you receive this training?
    a. Military
    b. School
    c. Boy Scouts
    d. Other (Please explain) ________________
    e. Answered no to question one
9. I have had training in Cartography.
    a. Yes
    b. No

10. If you answered yes to question five, where did you receive this training?
    a. Military
    b. School
    c. Boy Scouts
    d. Other (Please explain) ________________
    e. Answered no to question one
11. Have you ever participated in any orienteering events (tests of navigational abilities, officially organized or informal)?
    a. Yes
    b. No
12. If you answered yes to question seven, could you briefly describe your experiences?
13. Have you ever participated in geocaching (use of a GPS device to find hidden markers)?
    a. Yes
    b. No
14. If you answered yes to question nine, could you briefly describe your experiences?
15. Would you describe yourself as a gamer?
    a. Yes
    b. No
16. How many hours do you spend on average playing action video games such as Halo, Gears of War, Call of Duty, etc. per week?
    a. 1-5 b. 5-10 c. 10-15
    d. 15-20 e. 20+
17. Have you ever played the game *Left 4 Dead.*
    a. Yes
    b. No

Survey of Spatial Education Results

Results here exclude comments for space concerns (most questions had no comments). The vast majority of comments reiterated answers expressed in the previous question.

	Questions														
Participant	1	2	3	4	5	6	7	8	9	10	11	13	15	16	17
1	N	E	Y	C	N	E	N	E	N	E	N	N	Y	B	N
2	Y	B	Y	C	Y	D	N	E	N	E	N	N	N	A	N
3	Y	A	Y	A	N	E	N	E	N	E	Y	N	N	A	N
4	N	E	N	E	N	E	N	E	Y	B	N	Y	N	B	N
5	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
6	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
7	Y	E	N	E	N	E	N	E	N	E	N	N	N	A	N
8	Y	BC	Y	C	Y	C	N	E	N	E	Y	N	N	B	N
9	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N

	Question														
Participant	1	2	3	4	5	6	7	8	9	10	11	13	15	16	17
10	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
11	N	E	N	E	N	E	N	E	N	E	N	N	Y	B	N
12	Y	ABC	Y	ACD	N	E	N	E	N	E	Y	Y	N	A	N
13	N	E	N	E	N	E	N	E	N	E	N	N	N	B	N
14	N	E	N	E	Y	D	N	E	N	E	N	N	Y	B	N
15	N	E	N	E	N	E	N	E	N	E	N	N	Y	B	N
16	N	E	N	E	Y	D	N	E	N	E	N	N	Y	B	N
17	Y	B	N	E	Y	B	Y	B	Y	B	Y	N	N	B	N
18	N	B	Y	B	N	E	Y	B	N	E	Y	N	N	A	N
19	N	E	Y	B	N	E	N	E	N	E	Y	N	N	A	N
20	Y	D	N	E	Y	D	N	E	N	E	N	N	N	B	N
21	N	E	N	E	N	E	N	E	N	E	N	N	Y	C	N
22	N	E	N	E	N	E	N	E	N	E	Y	N	N	A	N
23	Y	B	N	E	N	E	N	E	N	E	N	N	N	A	N
24	Y	B	Y	B	Y	B	N	E	N	E	Y	N	Y	B	N
25	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
26	N	E	N	E	N	E	N	E	N	E	N	N	Y	B	N
27	N	E	N	E	N	E	N	E	N	E	Y	Y	N	A	N
28	N	E	Y	AD	N	D	N	E	Y	A	Y	N	N	C	N
29	N	E	N	E	Y	D	N	E	N	E	N	N	N	A	N
30	N	E	N	E	N	E	N	E	N	E	N	N	Y	A	N
31	N	E	Y	D	N	E	N	E	Y	D	N	N	Y	B	N
32	Y	C	Y	C	N	E	N	E	N	E	Y	N	N	A	N
33	Y	B	Y	B	N	E	Y	B	Y	B	N	N	N	A	N
34	Y	B	Y	B	Y	B	Y	B	Y	B	N	N	N	A	N
35	Y	A	Y	A	N	E	N	E	N	E	Y	N	N	A	N
36	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
37	N	E	Y	C	N	E	N	E	N	E	Y	N	Y	C	N
38	Y	B	Y	B	Y	BD	Y	B	Y	B	Y	Y	N	A	N
39	Y	A	Y	A	N	E	N	E	N	E	Y	N	N	A	N
40	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
41	Y	B	Y	B	Y	D	Y	B	Y	B	N	Y	N	B	N
42	N	E	N	E	N	E	N	E	N	E	Y	N	N	B	N
43	Y	B	Y	B	Y	B	Y	B	Y	B	Y	N	N	A	N
44	Y	C	Y	C	N	E	N	E	N	E	N	N	N	C	N
45	Y	BC	Y	C	Y	B	Y	B	Y	B	Y	Y	Y	B	N
46	N	E	Y	C	N	E	N	E	N	E	Y	N	N	B	N
47	Y	B	Y	D	Y	BD	Y	B	Y	B	Y	Y	Y	A	N
48	Y	B	Y	BC	Y	B	Y	B	Y	B	Y	N	N	A	N

	Question														
Participant	1	2	3	4	5	6	7	8	9	10	11	13	15	16	17
49	Y	B	Y	B	Y	B	Y	B	Y	B	N	N	N	A	N
50	N	E	N	E	N	E	N	E	N	E	N	N	N	A	N
51	Y	BCD	Y	BC	Y	BCD	Y	B	Y	B	Y	Y	N	A	N
52	Y	B	N	E	Y	B	Y	B	Y	B	N	N	Y	A	N
53	Y	B	Y	B	Y	B	Y	B	Y	B	Y	N	N	A	N
54	Y	A	Y	A	Y	AD	N	E	N	E	Y	N	N	A	N
55	Y	B	Y	B	Y	B	Y	B	Y	B	N	N	Y	C	N
56	N	B	N	B	N	A	N	B	N	E	N	N	N	B	N
57	Y	BCD	Y	B	Y	B	Y	B	Y	B	Y	Y	N	B	N
58	N	B	N	E	N	E	N	E	N	E	Y	N	Y	C	N

Appendix B - Test instruments

Direction Estimation Task

Participants were asked to estimate the direction to a landmark based on the location of a second landmark. They were given a sheet with six copies of the following figure on it:

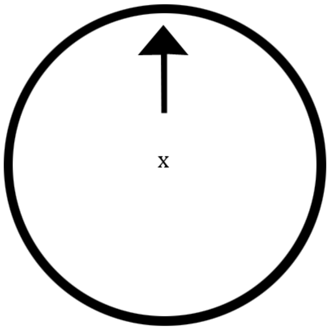
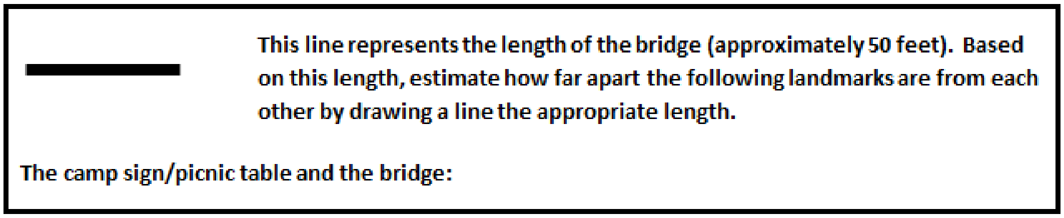


Figure B.1 – Direction Estimation Figure

They were then asked to imagine that they were standing on the x in the middle of the circle. Two landmarks from the experimental environment were presented, and the participants were asked to imagine that the first is directly in front of them (in the direction the arrow is pointing). They were then asked to draw an arrow indicating the direction the second landmark is in relation to them (the x) and the first landmark (the arrow).

Distance Estimation Task

Participants were asked to estimate the distance between two landmarks in the virtual environment. They were presented with the bridge landmark as a reference, as the bridge is approximately 50’ long. After being presented with the reference landmarks, eight pairs of other landmarks were listed and the participants were asked to estimate the distance between the two. An example of the instructions and a pair of landmarks is displayed below:



This line represents the length of the bridge (approximately 50 feet). Based on this length, estimate how far apart the following landmarks are from each other by drawing a line the appropriate length.

The camp sign/picnic table and the bridge:

Figure B.2 – Distance Estimation Figure

Appendix C - Images of the virtual environment

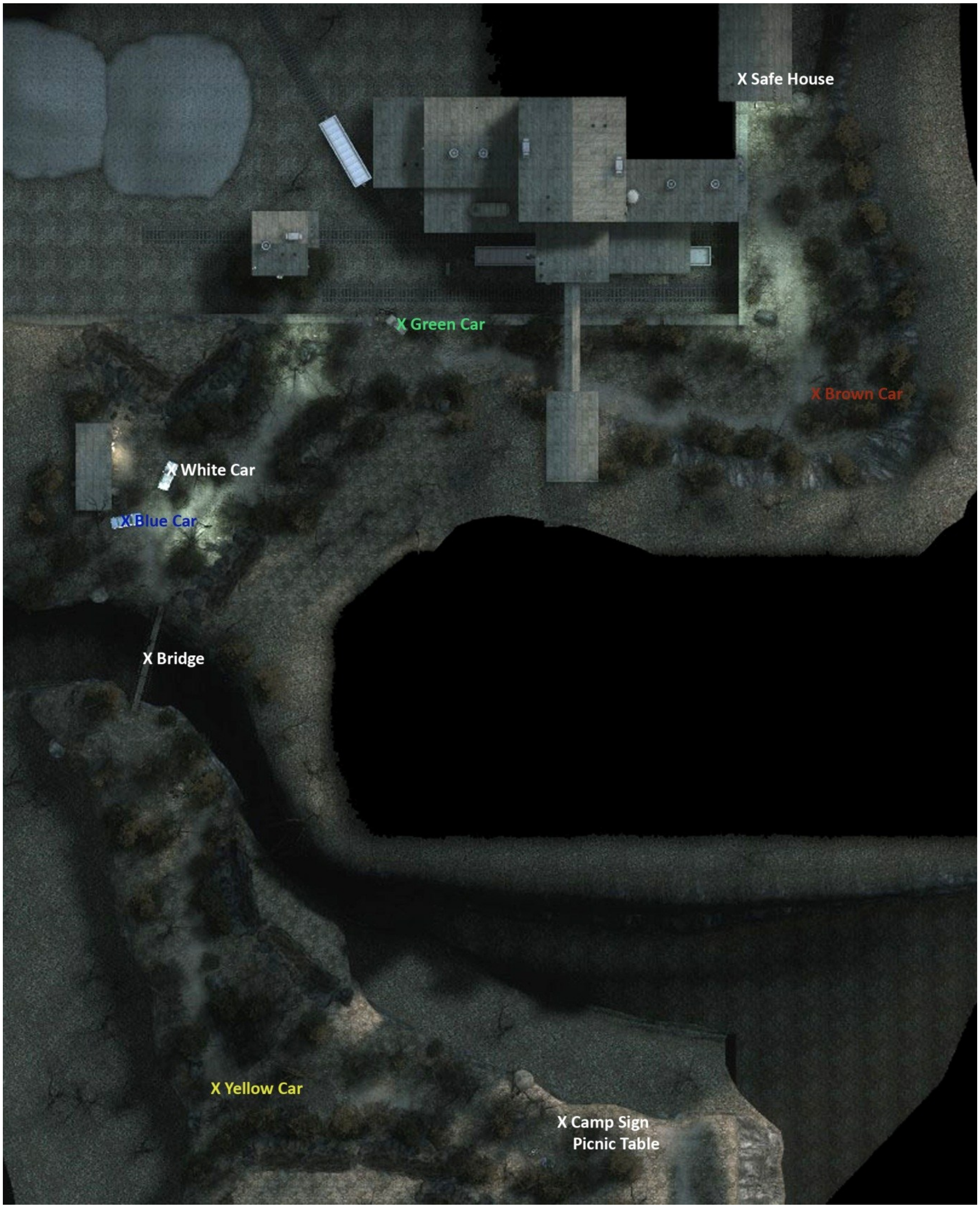


Figure C.1 – The official map showing the location of the eight landmarks.

In-game views of the eight landmarks:

Figure C.2 – Landmark 1 – The camp sign with picnic table.

Figure C.3 – Landmark 2 – The yellow car.

Figure C.4 – Landmark 3 – The rope bridge.

Figure C.5 – Landmark 4 – The blue car.

Figure C.6 – Landmark 5 – The white car.

Figure C.7 – Landmark 6 – The green car.

Figure C.8 – Landmark 7 – The brown car.

Figure C.9 – Landmark 8 – The ‘safe house’ with the red metal door.