Navigation and Wayfinding in Virtual Reality: Finding the Proper Tools and Cues to Enhance Navigational Awareness

by

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I dedicate this work to all of my nieces and nephew; Lauren Brooks, Jake Vilha, Ruby Birrer, Kristen Brooks, and Chloe Daggett. I hope you will always be curious and full of questions, and remember that only your dreams and hard work will stop you from reaching your goals.

CHAPTER 1

Introduction

Virtual Reality (VR) has been described as “a magical window onto other worlds, from molecules to minds,” (Rheingold, 1991). VR been proclaimed to change the way we might learn by the way people visualize and interact with objects. A major component of this visualization is the ability to view the virtual environment from different perspecties. These perspectives include exploring the environment in an egocentric manner, flying above the environment to gain an exocentric viewpoint, or combining the exocentric view with the egocentric view. Obvious questions arise with so much visual orientation potential: Will the participants know where they are in a large-scale virtual environment? Will they know where other objects or locations are? Will they recognize what objects they are looking at? Finally, does experiencing a synthetic environment lead to similar behaviors a person would have in the real world under similar circumstances?

To answer these questions we have to look into the literature of human behavior in navigation and wayfinding in the real world, and compare it with behaviors exhibited in virtual reality. If the behaviors match, then we can apply navigational tools that are enlisted to aid in navigation awareness in the real environments, and apply them to virtual environments. If the behaviors are not alike then the differences must be understood so that appropriate actions can be undertaken to ease the navigation and wayfinding experience for the participant in the virtual environments.

In the real world, wayfinding behaviors can be affected by varying exploration conditions and varying navigational tools (Butler, Acquino, Hissong, and Scott, 1993; Sonnefield, 1985; Goldin and Thorndyke, 1984). Research in this field has been difficult in the past because of lack of control over the environment being examined, the expense in changing the environment, and lack of control over exposure time to the environment (Peponis, Zimring and Choi, 1990). It is because of these reasons that navigation and wayfinding have also been studied using simulations of real and imaginary environments, (Goldin and Thorndyke, 1982). These studies have also been hindered because of the media used, such still photographs, film and drawings (Thorndyke and Hayes-Roth, 1982; Infield, 1991). Peponis et. al., (1990) summarize some of the problems in stating that "direct observation of wayfinding is relatively rare and it is not always clear what is being recorded and what is being analyzed." Because the findings in these domains are problematic, an in depth look at the experimental studies is needed.

Chapter One defines the terms used in this thesis. Chapter Two reviews the literature pertinent to these areas and the metrics used in these studies. Chapters Three and Four will describe a research study conducted in virtual reality and further issues that must be addressed.

Definition of Navigation Terms

Navigational Awareness

Navigational Awareness is defined as having complete navigational knowledge of an environment. There are two distinct types of navigational knowledge of an environment and each type affords different behaviors. The first type of navigational knowledge is called procedural knowledge or route knowledge. Procedural knowledge is ego-referenced and is usually gained by personal exploration of a new area. The characteristics of procedural knowledge are that the navigator can successfully go from one landmark to another on a known route, but does not recognize alternate routes, such as short-cuts. A person who has procedural knowledge may know the approximate distance between the landmarks along the route they traveled. The reason for better judgment of distance for a specific route traveled is because learning is formed by sequential travel (Allen and Kirasic, 1985). Knowledge of relationships of places along this route are unidimensional, a person will be better at recalling when it is in the direction they learned the route (Allen and Kirasic, 1985).

Survey knowledge, the second type of navigational knowledge, is attained by multiple explorations of an environment using multiple routes. Survey knowledge is characterized by the ability to take an exocentric viewpoint and is therefore world referenced. The mental representation of an area is seen from a bird's eye point of view. This is similar to having a mental representation of a physical map (Goldin & Thorndyke, 1982), which is sometimes referred to as a cognitive map. Having procedural knowledge does not guarantee survey knowledge, although it is very probable that this will happen (Moeser, 1988). When survey knowledge is built by personal experience through exploration, it is referred to as a "primary" experience (Presson & Hazelrigg, 1984). Survey knowledge can also be built in a "secondary" manner through map or picture study alone (Goldin & Thorndyke, 1982) (Thorndyke & Hayes-Roth, 1982). Presson & Hazelrigg (1984) and Scholl (1993), have shown survey knowledge gained in this manner is inferior to primary survey knowledge. The inferiority arises in the orientation and location of landmarks. When a person has both procedural knowledge and primary survey knowledge, they have complete navigational awareness. The characteristics of survey knowledge are that distances between, and location of, landmarks are known and routes can be inferred even though they have not been traveled before. The benefits of survey knowledge come into play when procedural knowledge is not sufficient. An example of this is when there is a large traffic back-up on the route someone travels daily. A person with survey knowledge may try a different route with success even though they have never traveled it before.

The research in navigational awareness has shown that to achieve complete navigational knowledge in a new large-space environment, a person has to go through a constructive dynamic process. This process is described in a model from Siegel & White, (1975), called the "Sequential and Hierarchical" model. The first two steps are necessary for procedural knowledge and the third and fifth for complete survey knowledge.

1. Landmark recognition: Objects become landmarks for two reasons; their distinctiveness and personal meaning (Lynch, 1960). The objects can be distinctive for example, because of their architectural style, their size, or color (Weisman, 1981). These distinctive objects become salient landmarks especially when they also give directional information, such as being on a corner of two perpendicular streets. Objects that have personal meaning also become salient landmarks, even though they many not have directional meaning (Infield 1991).

2. Routes or Links: Routes and links are formed when traveling between two landmarks. At this point relative distance between two landmarks on a traveled route is achieved. While forming route knowledge, images and landmarks are recalled, if asked for in the same manner as the route is traveled.

3. "Primary" Survey knowledge: This type of knowledge is achieved after significant traveling of routes and links to the point where alternate routes can be inferred and straight line distances between landmarks can be determined.

4. "Secondary" Survey knowledge: This step is not part of Siegel & White's model, but has been added because partial survey knowledge can be attained.

It is also very unclear where secondary survey knowledge falls in this continuum. Secondary survey knowledge involves using only maps to learn about an environment. Distance between landmarks is achieved but their alignment or absolute location may be faulty. When distance or routes are curvy they may be underestimated also (Wickens, 1991). This short-cut to survey knowledge may inhibit further progression until one back tracks and gains procedural knowledge.

5. Chunking of the environment: If the environment is extremely large it becomes necessary to chunk the environment into smaller regions. Landmarks located in different regions maybe susceptible to slight distance distortions (Wilton & Pidcock, 1982) (Steven & Coupe, 1978). These smaller regions then become nested into larger regions, and so on. An example of this type of chunking is; several neighborhoods that could be nested under a town, a county, under a state, under a country. This nesting ability gives us the ability to mentally zoom in and out of representations to give distance or direction to another target. As we zoom out though, we lose granularity of detailed description (Wilton, 1977). According to Infield (1991), the representation that one would use will be the one which is similar to the level of the target space. To transition from one layer of representation to another, a common feature must be recognized in both representational layers. This common feature then becomes the link between the two.

Landmark knowledge is tested through the landmark recognition task, the landmark placement task, and landmark orientation. The landmark recognition task requires a person to distinguish between sights that have and have not been seen during exploration. The landmark placement task involves having subjects place landmarks in their proper position on a map. The orientation task is also referred to as the directional pointing task. This task can be executed in a variety of ways, but the essence of the task is test whether a subject knows where a landmark is in relation to other objects. The angle between where the subject points to and the angle to the landmark is calculated.

Route knowledge is commonly tested in two different manners. The first method is called the route distance estimation task. This involves asking a subject to give an estimation of distance between two objects or between themselves and an object. The second method is called landmark sequencing. The subjects in this type of task would be given pictures of two landmarks located on a route and then asked which landmark would be encountered first.

Survey knowledge is usually tested by the Euclidean distance estimation task. Similar to the route distance estimation task, the Euclidean distance estimation task involves giving distance estimates between two objects or between oneself and an object. The distance this time would be a straight line or "as the crow flies" distance. Survey knowledge can also be measured by having subjects infer a route between two objects if the common route is blocked.

Spatial Ability

The definition of spatial ability is tenuous at best, as it has been studied for most of this century, and to this date a consensus has not been reached and remains an "ill defined concept" (Pellegrino and Goldman, 1983). What is agreed upon is that spatial ability is comprised of various dimensions. The three major dimensions of spatial ability that are commonly addressed are spatial orientation, spatial visualization and spatial relations (Lohman, 1979). Spatial orientation involves the ability to mentally move or transform stimuli, while retaining their relationships. Spatial orientation also involves the mental manipulation of an object using oneself for reference. Spatial visualization goes further, in that the person can manipulate the relationships within an object. The third dimension, spatial relations, consists of the ability to imagine how an object will align from different perspectives.

Spatial ability is usually measured by psychometric tests. A problem with these tests is that they present problems using small scale objects (Eliot, 1987), whereas most of our interaction with the real world is in large-scale spaces. Small scale refers to an object or environment that can be seen in its entirety from at least one viewpoint. Large-scale spaces must be learned from sequential exposures (Infield, 1991). It was not until recently that one of these spatial ability tests, the Guilford-Zimmerman Spatial Orientation Test was shown to predict performance in a large scale space (Infield, 1991). At present, the other psychometric tests measuring spatial relations and visualization have not been validated for large-scale space performance.

Wayfinding

Wayfinding as defined by Gluck (1990) is “the process used to orient and navigate. The overall goal of wayfinding is to accurately relocate from one place to another in a large-scale space”. Peponis, et. al., (1990); describe wayfinding as “the ability to find a way to a particular location in an expedient manner and to recognize the destination when reached”. Downs and Stea (1973), proposed that this is done in four steps.

1. Orientation: Determining where one is in respect to nearby objects and the target location.

2. Route Decision: Choosing a route that will get one to their destination.

3. Route Monitoring: Monitoring the route one has taken to confirm that one is on the correct route and is going in the right direction.

4. Destination Recognition: Recognizing that one has reached the correct destination, or at least a point nearby.

The first step of this model infers that some landmarks must have been distinguished and selected by the wayfinder. The person knows what the landmarks are, where they are, and their relative position in relation to their own location.

Definition Summary

In summary, Spatial Ability is perceiving the environment through our senses, the cognitive process of how we learn our environment, and the relationships between objects. Spatial Awareness is how well we perform in the world, or under experimental conditions using our spatial ability. Navigational Awareness is the result of exploring an environment well enough to have both procedural and survey knowledge of it. Wayfinding is the dynamic process of using our spatial ability and navigational awareness of an environment to reach a desired destination.

Definition of Architectural Terms

The research in this study took place in a virtual building. The design and construction of the building was based upon elements discussed in the literature pertaining to wayfinding in architectural structures. The major impetus of this work in the field of architecture has been lead by Evans (1980, 1982, and 1984); Garling, et. al., (1986); and Peponis, et. al., (1990). In most situations architects want to design a building to reduce wayfinding problems for the people working or visiting the building. Two types of cues are employed to achieve this end. Navigational cues may either be intentionally built into the structure or later added to it (such as labeling room numbers, or naming buildings). The cues built into the structure are differentiation, visual access, and complexity of the layout (Garling, et. al., 1986). Differentiation refers to different sections of a building being distinguishable. This can be achieved by varying size, form, architectural style and or color (Evans, 1980, 1982 and 1984).

Visual access pertains to whether different areas of the building can be seen from other areas. To increase successful navigation a person should be able see parts of the environment from many vantage points (Garling et. al., 1986). Good visual access in a building can be achieved by having an open area that can lead to many other areas of the building. Visual access can also include the ability to see outside the building by using windows or portals. For an outdoor environment this could mean access to a tall building or hills from which to view the environment.

Complexity refers to the layout of the building or environment. A simple layout would be one that has good visual access, right-angle intersections, and few segmented hallways (Peponis, et. al., 1990). A detailed description of how these three navigational cues were incorporated into the environment used in this study can be found in Chapter 3.

CHAPTER 2

Literature Review

This review of the literature will report the effects of two different ways of presenting environmental information; map study and exploration.

Navigation

Thorndyke and Hayes-Roth(1984), compared subjects who had navigational experience in a building but had never seen a map of that building, to subjects who had seen a map of the building, but had never been in it. The subjects who had navigational experience were employees who worked in the building. They were separated into three groups depending on their time of exposure to the building (1-2 months, 6-12 months, 13-24 months). The subjects who studied the map were psychology students, and they were also were split into three groups. The three map study groups were required to study the map of the building till they could recreate the map without error. The first group's exposure to the map was stopped at this point, while the second group received 30 more minutes to study the map and the third group an additional 60 minutes. The tasks for all subjects were to give judgments of route distance and Euclidean distance for 42 pairs of locations and for targets on a map to engage in directional pointing, simulated orientation and location of target location.

There was no difference in performance between the map-study groups. This finding suggests that once a person has studied a map to an error free criteria their navigational knowledge does not progress beyond that point. The map-learning subjects made larger errors in route estimations than Euclidean distance estimations. The navigation subjects showed the opposite effect; larger errors for the Euclidean distance than for route estimation distance. The group that had only one to two months exposure had greater Euclidean distance judgment errors than those who had more experience. Those in the navigation condition who had at least 6 months experience performed on an equal basis as those in the map-learning condition for giving Euclidean distances. This group also did better on the route estimations than the map-learning subjects. The orientation tasks provided evidence that Euclidean representations are better learned from direct experience then secondary survey knowledge. For both orientation tasks the navigation subjects were more accurate than the map-learning subjects. For object location, the most experienced navigation group performed equally well as the map-learning group. The navigation group with the most experience overall performed better than any of the other groups. In summary, the most experienced navigation group attained complete navigational knowledge, and primary survey knowledge was superior to secondary survey knowledge.

Goldin and Thorndyke (1982) examined the different types of knowledge developed from a direct navigation experience and from a simulated experience. The direct navigation experience involved a bus tour of an area. The simulated experience was a filmed auto trip of the same area. In both tours the subjects were passive observers. An additional factor was the other type of information subjects received, a verbal description during the tour, prior map study or no additional information. The map study consisted of looking at a map with landmarks and routes for 10 minutes prior to taking the tour. The narrative provided during the tours gave names of the streets on the route, landmarks, the distance between intersections and the current compass direction.

Participants performed 6 tasks after the tour. The tasks were; location recognition, location sequencing, landmark location, route and Euclidean distance estimations and taking a basic spatial ability test. The spatial ability test was the Kit of Factor-Referenced Cognitive Tests (French, Ekstrom, and Price, 1963). These are tests of visual memory, spatial visualization and perceptual independence abilities.

The subjects in the film group identified tour locations better than those who were on the actual tour. Within the film group the control group performed better than the two groups with added information, narration and map study. This was not the case for the subjects on the real tour, where there was no difference. For the location-sequencing task film groups again performed more accurately than the those on the real tour. The narrative condition had a negative effect in performance across both conditions. The orientation test provided opposite results. Those on the real tour were about 10 degrees more accurate than those in the film group. While both groups contained subjects who were more than 90 degrees off the mark (complete disorientation, Ciccone et. al., 1978), there were significantly more subjects in the film group who were disoriented than in the real tour group. Both the film and the real tour groups who were allowed to study a map beforehand, did worse on the orientation task than those in the control and narrative groups. The route distance estimation tasks revealed no differences between the groups.

Landmark placement and Euclidean estimations tasks also showed no differences between the film and tour groups. In post-hoc tests though, differences did appear for those in the film group having access to additional information. Those who had the map to study beforehand showed a higher performance than all of the other five groups, and those who had the narrative had a lower performance than the other five groups.

The results of the study indicate that people can learn about environments from a simulated medium such as film. In both conditions though, the subjects were passive. Thorndyke suggests that interaction, either by a person driving the tour or interacting with the environment in a simulation, might show different results. The results of this study also show that within a condition, such as the film condition, adding an additional navigational aid has consequences and that the consequences are task dependent. In one test we see that having a map or narration hinders performance, while in another task the map improves performance and narration lowers it. These results are important when deciding what aid to use to introduce someone to a new environment.

Wayfinding

In 1985 Streeter, Vitello and Wonsiewicz performed a wayfinding study comparing navigational aids for people driving in a car. There were 7 routes chosen for the subjects to drive. They ranged from 3 to 20 miles. The routes were divided into three categories. The first category, limited access, was defined as one that used the major highway for more that 50% of the route, but contained seven turns within the route. The second category, moderately difficult were local routes where each had 6 turns. The final category, were complicated local road routes where each had 13 turns. There were 2 routes for each category, and a subject was asked to drive 1 of the 2 routes from each category. All subjects also drove a trial route that was four miles long and contained only three turns. The comparison was between those who had a tape recorded narrative of where to go, those who had a customized route map of the area, those who had both, and those who had none. In the last condition, the drivers were instructed to use any method they wanted to find their way using a standard road map. The measures recorded were time (seconds) to target, mileage, number of turns, and errors. Errors included turning in the wrong direction, turning on the wrong street, and passing the destination. For the drivers who had the tape recorder, the number of rewinds was also recorded. The experimenter sat silently in the back seat during the test.

The control group, those without any navigational aids given to them by the researcher, drove significantly more miles, took more turns than necessary, and took more time completing the task, than the other three groups. Within the experimental conditions those who had the narrative drove fewer miles than those with the customized map. The narrative group also took marginally less time than the customized map group. The customized map group made significantly more errors than both the narrative group and the customized tape - narrative combination group. The combination group made marginally more errors than the narrative only group.

This study showed that while wayfinding it is more difficult to interpret a map than it is to receive directions. The finding that the combination of tools did not produce better performance than the narrative alone is what is important, since more tools may not mean better performance.

Regian and Shebilske (1990) conducted studies of the use of VR as a training medium for visual-spatial tasks. One of their experiments involved wayfinding. The environment used in the wayfinding study was a virtual maze. It consisted of three stories, with four rooms in each story. Each room was the same size and each contained a unique color-coded object, either a star, cube sphere, or pyramid. The color could be red, green or blue. Every room was connected to at least one adjoining room by a hallway or passageway leading to a room above. The walls were all colored gray, the floors red and the hallways yellow. Subjects were given verbal directions on where to move through the virtual environment. Three different tours were taken. Following the tours the subjects were free to self-explore the environment for one hour. The testing phase of this experiment consisted of 3 wayfinding tasks. The subject started in one room of the complex and then tried to take the shortest path to a room having a target object. The first route could be completed by visiting a minimum of eight rooms, the second route in four rooms and the third route in six rooms. A perfect result would mean that all of the rooms would be visited at least once for a total of 18 rooms. The dependent measure was the number of rooms traversed for each wayfinding task.

The authors performed a comparison between these data and data from a random walk algorithm and found significant differences. The results of this study showed that the mean number of rooms for each tour was 10.1, 4.8 and 6.7. The authors claim that this shows that subjects can learn navigation spatial-navigational skill in a virtual environment. However, their design and methodology does not support this claim. The major problem was the Monte Carlo method used to show that learning occurred. By using this method a person could enter a total of 14 rooms for the first tour (8 rooms was the minimum) and still show a significance learning effect. The performance in the last tour (6 rooms minimum) could not be ruled out by chance. Previous research has already shown that “people do not act like randomly moving automata that make unbiased decisions at each point where a decision has to be made” (Peponis, et. al., 1990). Two rules that Peponis observed in wayfinding behavior, is people avoid unnecessary backtracking and also that people tend to find the area that gives them the best visual access to other areas. Regian, et. al., should have run a control group for the same wayfinding task. The control group would have had no experience in the building, and therefore would have had to search for the unique object, using strategies that would probably be much more efficient than a random search.

Butler, Acquino, Hissong and Scott (1993) conducted 4 experimental studies examining newcomers wayfinding in a complex building. Only the first three studies will discussed. Their first study examined whether signs or the use of You-Are-Here (YAH) maps would benefit people who were visiting a building for the fist time. These two experimental conditions were contrasted to a control group who had no added information. The dependent measure was the amount of time it took to reach two different rooms. The results showed that for the first room those with the maps took significantly longer than those who had no aids, and both of these groups took significantly longer than those who used the signs. For the second room, again those with the maps took longer than the other two groups. Those who used the signs did not differ from the control.

The second study by Butler et. al., (1993), was initiated because there were multiple routes to most locations in the building, and the best signed route had to be determined. This study examined possible routes to see if people preferred, and would use, the simplest (those with the least decision points) or the most efficient (the shortest distance). Subjects examined 7 routes leading to one location, by viewing a video tape of each route. While the video tape was playing, appropriate floor plans would be displayed, and a narrative was heard pointing out turns, decision points, etc. Subjects were then asked to rate each route on a scale of 0 to 10 with 0 being a route they would never take and 10 being the best route. After rating the routes for their personal preference, subjects were given comments about each of the routes by people who were confined to a wheelchair or visually impaired. The subjects were then asked to rate the routes as if they were confined to the wheelchair and then as if they were visually impaired. A final rating was then requested for the best overall route keeping all of the factors they had learned about in mind. The results showed that the subjects preferred routes that conserved energy (the shorter routes), regardless of how complex they were. Significant rating changes were made depending on the physical impairment being asked about. The final ratings showed that the shortest routes were picked but weighted more for those in a wheelchair than those visually impaired.

The third study generalized the results of the second. The second study only looked at routes that were going to one location, while the third study examined a single starting point with two routes going to 2 different locations. Subjects were told that the end locations were either bathrooms or vending machines. The routes were not real routes but were derived by crossing complexity ratings (Leeuwenberg, 1967) and distance. Subjects reviewed 56 pairs of routes and again distance was found to be the significant factor that determined which path they chose. Shorter distances were chosen despite their complexity. Both the second and third studies show that efficiency based on distance is more important than complexity. However the authors do raise the point that complexity may be more important for wayfinding in a building when verbal directions are given.

The wayfinding literature indicates that receiving directions verbally or through signs is advantageous when trying to find a goal. In contrast, the use of maps can be disadvantageous. What these studies did not do is have the subjects repeat their performance without any navigational aids in order to test their navigational awareness. This factor may not be important in structures that are rarely visited, but ideally for people who work in a building this factor could be important, such as during an emergency in a hospital, or if a building was on fire. A person may not have the time or opportunity to read signs in a building or ask directions. A series of studies conducted by Moeser (1988) tested student nurses in a hospital and the results showed that they did not have survey knowledge of the building even after 3 years. Moeser mentions anecdotally that the nurses verbally reported to her that they use the signs in the building to locate areas within the hospital. Which may be evidence that having signs relieves the cognitive load to the point where survey knowledge is inhibited. The question that this thesis will address is, what navigational tools under different exploration conditions would benefit wayfinding at a later period where the tools would not be available.

Darken and Sibert, (1993) reported on an informal study looking at toolsets for wayfinding in virtual environments. The tools available to the participants were flying (the ability to rise above the virtual environment), spatial audio markers, visual markers (breadcrumbs), coordinate feedback, grid navigation and two map-views of the world. The map-views available were track-up and North-up. Track-up maps change dynamically so that the user is always represented in the middle of the map, and the map revolves so that the users's forward view is always presented at the top of the map. A North-up map has a similar central representation of the user, but the representation rotates not the map. North is always representated at the top of the map. Only one type of map could be chosen and seen at one time. While the mechanics of how to use the tools were explained, the benefits and what information could be retrieved from them were not. Only one type of tool was available to the subject during each scenario for each condition. The environment was a large landscape with grid markings on the floor. The landscape was sparsely populated with objects such as ships and rectangles. The focus of this study was to examine how subjects would use a specific tool under three different types of conditions. The first condition was just to explore the environment. The second condition was a naive search, where the subject knew what the object looked like but did not know its location. The final condition was an informed search, where the subject knew both the description and location of the object. The subjects were instructed to search for the target. When the subject was close to the target a bell would sound and they were told to return to the starting position as efficiently as possible. The subjects were encouraged to talk aloud as they moved through the environment and as they used the navigation tool to help them.

The coordinate tools were mainly utilized in two ways. The first was at the start position, where the subject would move along one axis of the grid lined floor and note the feedback. During the return portion of the task they commented that they had remembered their initial position. The breadcrumbs were used more as landmarks than as trail making objects, which they were originally intended for. The first breadcrumb was usually dropped at the starting position. It was also observed that groups of breadcrumbs were dropped in a shape to show directional information.

Informal observations indicated that people used the different tools in a variety of ways. One of the most useful tools was a synthetic sun, which improved performance in both the search and return phases. In fact before the sun was added all subjects moved in the incorrect direction in the homing phase. The conclusion of this report was that subjects showed different behaviors when they used different tools in wayfinding.

Summary

The literature on navigation and wayfinding brings to light that at present we are unsure of how to introduce a person to new environments so that they will gain navigational awareness efficiently. The Thorndyke and Hayes-Roth (1982) and Goldin and Thorndyke (1982) studies show that exposure time and navigational tools can affect the process. Their studies revealed that map study before entering an environment can be beneficial but that when used alone it does not give someone complete navigational awareness. The research also points out that depending on the type of introduction to an environment, an additional navigational aid can have a positive or negative effect. The results also show that learning of an environment can occur without actually being there but the results do not reveal whether it is better to be an active participant or a passive observer when being exposed to a new environment.

The wayfinding literature shows that people are better at finding a target location when using signs or narrative directions than with using maps, and that adding navigational tools can have a positive effect or a negative effect depending on the task and the original tool or cue used. The research in wayfinding also showed that given a choice people prefer shorter routes to longer routes to a destination despite the complexity of a shorter route.

Both sets of literature point to a need to examine in further detail how to introduce someone to a new environment, what navigational aids are beneficial during initial exposure and their after-effects when the aid is may no longer available.

CHAPTER 3

The literature on navigation and wayfinding points to research questions that need to be addressed. The first question is whether navigation awareness is best attained by self-exploration of an environment or is better to be actively or passively guided? The second question is what navigational tools would be beneficial to navigational awareness? Previous research has shown that studying a map before entering an environment is helpful for creating secondary survey knowledge, but that secondary knowledge is inferior compared with primary survey knowledge. Previous research has also shown that having a map may or may not be helpful during an exploration period. The third question is what effects do these conditions and navigational tools have on wayfinding in the same environment at a later time?

Methodology and Procedures

The Environment

The virtual environment used in this research was a U shaped building that measured 100 feet by 100 feet (figures 1 and 3).

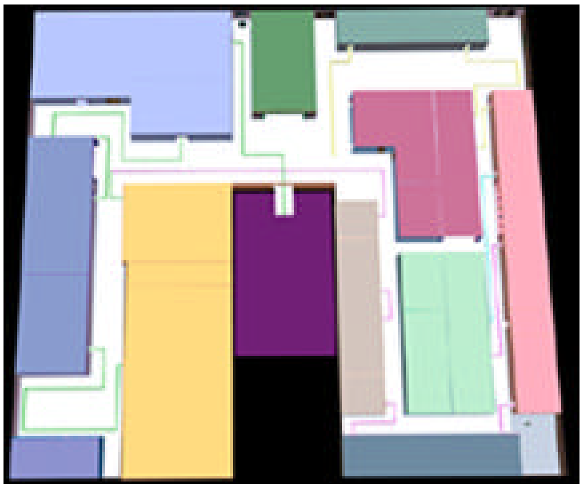

Figure 1 Bird's Eye View of Building (100ft x 100ft)

The walls, floors, and ceiling were modeled in Alias Studio (version 6), a 3D data modeling and animation software package. The virtual building was assembled and modified using Division's dVISE application software and custom user functions. The height of the building from floor to ceiling was 10 feet. The building contains 39 separate rooms with over 500 objects using approximately 50,000 polygons. Collision detection was incorporated so subjects could not walk through the walls, but was not incorporated for objects located throughout the building. Forty-four sensors were also created in Alias Studio and laid out on the floor. Stepping on a sensor would activate it and then the program would draw only those objects the subject could view from that sensor. This was instituted because Division software by default will draw every object in a world, which causes an increase of lag time between a subject's action and what they see as a result of their action.

Each room was populated using modified objects from Division demos. Paintings on the walls were either created using Adobe Photoshop or downloaded from WWW cites. The world was specifically designed to have some wide open spaces to allow visual access and distinctive areas (e.g., classrooms were located on one side of the building and offices on the other, Figure 3). Paintings and objects were located throughout the halls of buildings to be used as landmarks. No doors were used in this environment, as the interaction to open the doors was not intuitive and unnatural.

Apparatus

This study used Division's dVS software (version 2.0.4i) which ran on a SGI ONYX/2 RE2 computer graphics system.

The helmet mounted display (HMD) was the Kaiser Electro-Optics Inc., VIM 1000HRpv. The VIM 1000HRpv has a 100deg horizontal by a 30deg vertical field of view. It has a full color multiple active matrix, the LCD's contain 720,00 color elements or 240,000 color groups. The IPD was self adjustable by the participant. The total weight of the helmet was 26 ounces. This HMD is not stereo enabled which did not present a concern for this particular type of study[1].

The subjects moved in the direction their head was pointed. The subject's position and orientation in the world were afforded by the Polhemus Fastrak system,

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[1] Fred Books (1992) Final Technical Report to the National Science Foundation on University of North Carolina's Walkthough Project stated the following when reporting on stereopsis: "Stereo noticeably adds to the illusion of presence, but it makes much less difference in architectural modeling than in most applications. Architectural models have lots of parallel lines and planes, known to be perpendicular... Obscuration, perspective and the kinetic depth effect provide so strong a set of cues that stereo is almost frosting."

which monitored the position of the subject's head and of a 3-D joystick. A restriction on movement was placed so subjects could only move horizontally and not vertically. The 3-D joystick, also referred to as a wand, was manufactured by Division. The wand provided the subjects' movements in the virtual environment. The wand was configured so that only 3 buttons were active for this experiment. On top of the wand were three buttons laid out horizontally. The left button when pressed moved the subject forward and the right button when pressed moved the subject backwards. The middle button was disabled. On the front of the body of the wand were two buttons arranged vertically. The top button was not used in this study. The bottom button increased the speed of movement forwards or backwards, when pressed in conjunction with one of the directional buttons above.

The experimenter's workstation consisted of a computer keyboard and a VGA computer monitor. The monitor presented the real-time imaging of what the subject was seeing in the virtual environment.

The Experimental Design and Independent Variables

A 3 X 2 X 2 between subject factors design was used (Table 1). The first factor was type of exploration; self-exploration (SE) where the subjects was free to explore the building in any manner they wanted, Active Guided (AG) where the subject would follow a pre-determined path using the wand, and Passive Guided (PG) a guided path where the subject would be moved through the environment at a constant speed with no interaction. (The path layout can be seen in figure 2.) The final condition was the Control group who did not explore the environment but only studied a map of the building.

Table 1 Experimental Design Layout

	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	MB
Map During							N/A
no Map During							N/A

In the SE condition, subjects were given one half hour to explore the building, moving the environment in any manner they chose. In the AG condition, the subjects were instructed to follow the path drawn on the floor and to not deviate from it. The path was laid in 90 degree angles going into or passing the doorway of every room. The AG subjects were also given one half hour to explore the building. If they finished before the 30 minute time limit they were to begin the tour again. In the PG condition, the subjects were moved along the path at a constant velocity, so that tour took a total time of 30 minutes and 8 seconds. These subjects were allowed to move their head and look in any direction they wanted to, much like a passenger in a car.

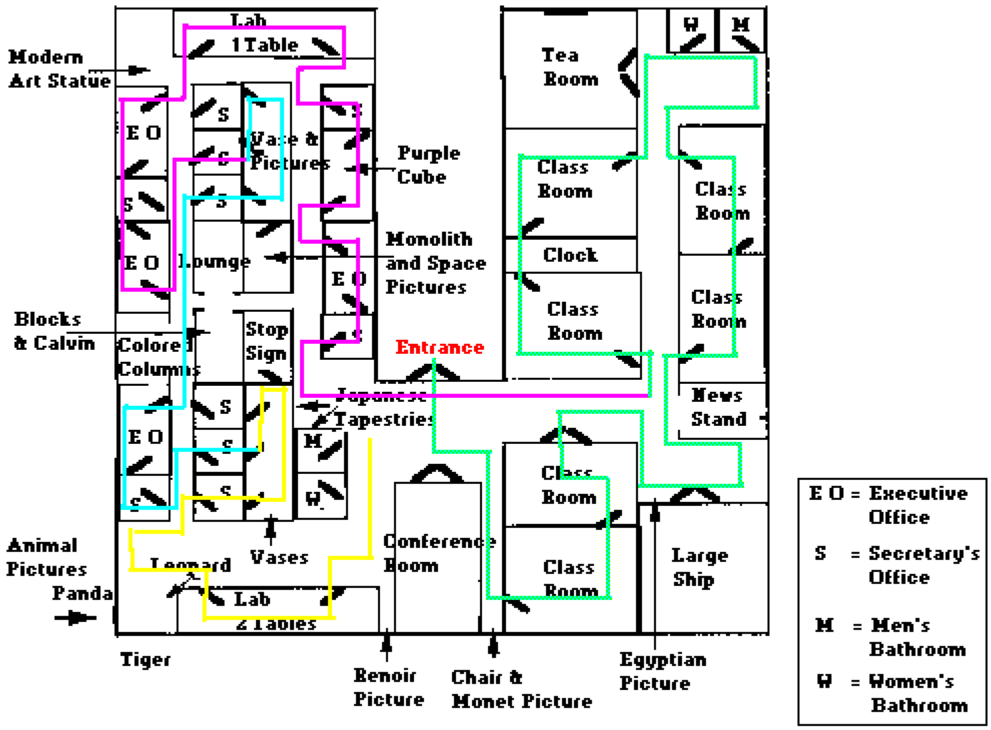

Figure 2 Path layout for Active and Passive Guided Tours (begins with the green line)

The second factor was access to a map (figure 3) of the building for five minutes before entering the virtual building. There were two conditions; having a map vs. not having a map.

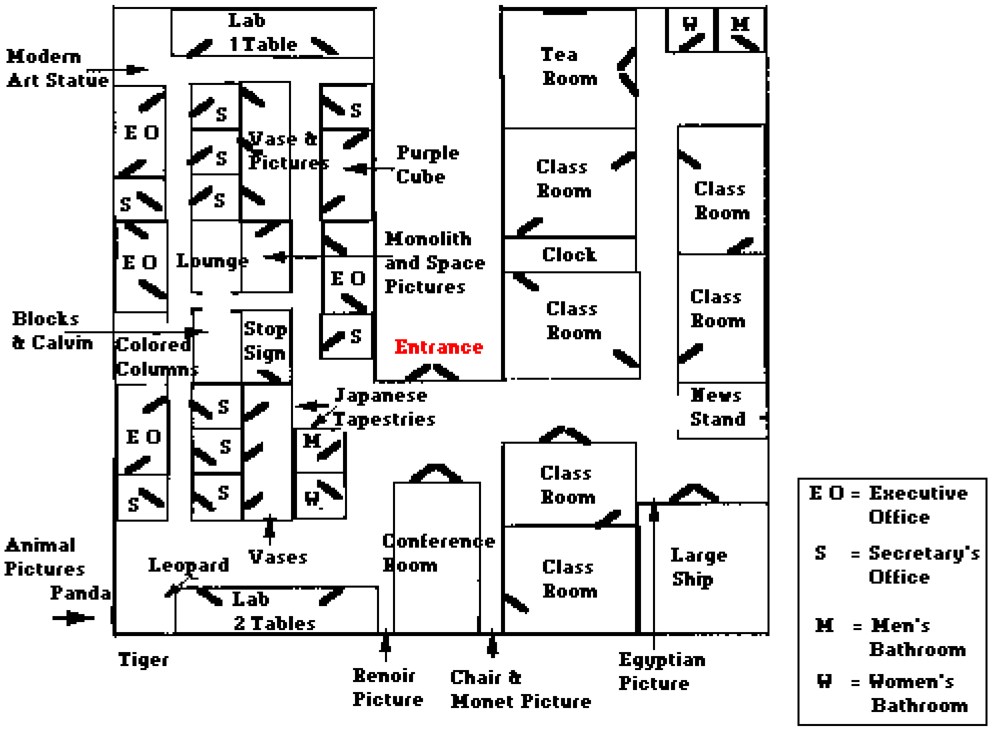

Figure 3 Representation of the Map given to the Subjects to Study Before they entered the Environment

The third factor is whether or not subjects were given a map during the exploration phase of the environment (figure 4). This map only showed the configuration of the building. The map was attached to the subject's view much like a heads up display. It was located in the lower right field-of-view and had a red crosshair that moved as the participant moved. The crosshair allowed the participant to see their position in the world at all times, but did not show their orientation. The map was a North-up map. Images of how the experimental conditions appeared in the actual virtual environment can be seen in figures 5-8.

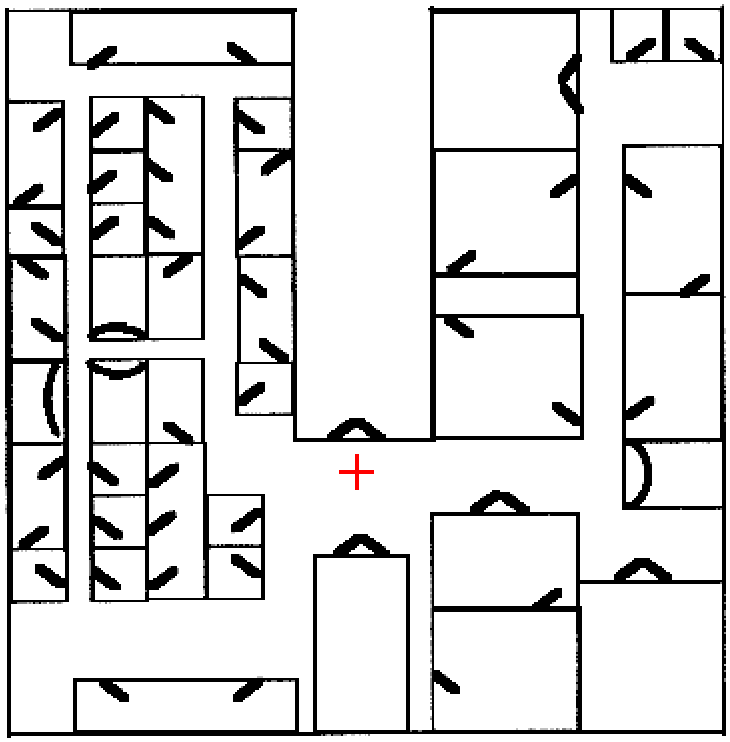

Figure 4 Representation of the Map used During Exploration (crosshair showing position)

There was also one control group run in this experiment who performed the same tests as the experimental groups. This control group had only the map to study before entering the environment to be tested, without the benefit of exploration. This group was essential because it provided a baseline against which all the exploration groups could be compared.

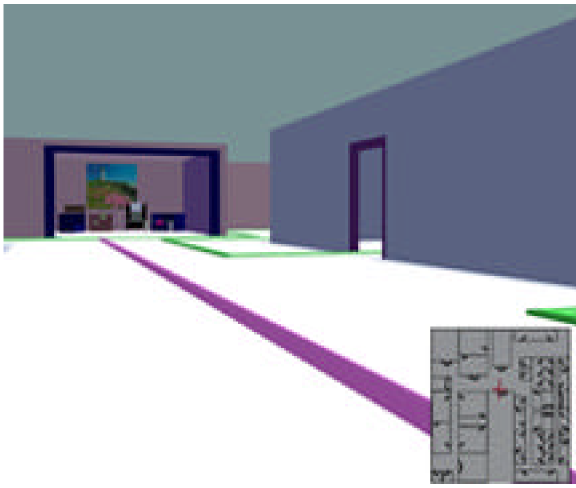

Figure 5 Guided Tour & Map During

Figure 6 Self Exploration & Map During

Figure 7 Guided Tour (No Map)

Figure 8 Self Exploration (No Map)

The Metrics and Dependent Variables

<u>*Guilford-Zimmerman Spatial Orientation Test*</u>

The first test taken by the subjects was the Guilford-Zimmerman Spatial Orientation Test. The GZ was used as a covariate for all other metrics tested.

The Directional Pointing Task or Orientation Task

The subjects were initially placed at the Entrance Door. They were then asked to look in the exact direction of three different objects located in areas of the building not in their field of regard. When they felt they were looking at the object their absolute angle of departure from the actual location was recorded. Any angular disparity within 5 degrees was counted as an exact match. Any angular disparity over 90 degrees was counted as complete navigation disorientation. If subjects reported that they did not know where the object was located they were asked to guess. (A Map of the building and the objects used in this task to can be seen in Figure 9)

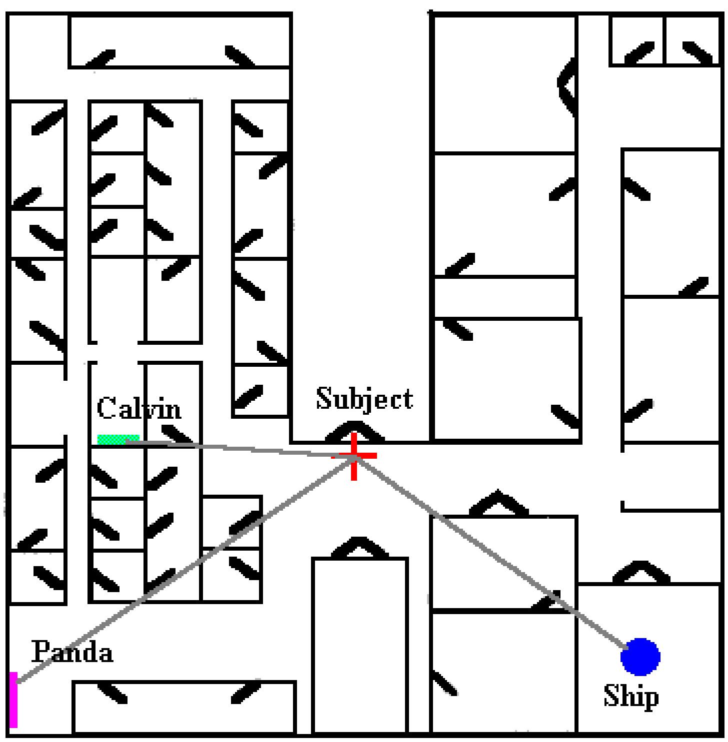

Figure 9 Objects used in the Orientation Task

Route Distance Estimation

Two types of route distance estimations were used. The first was between an object and the subject, and the other was between two objects. The participants were taken out of the virtual environment after the orientation task and then asked to give an estimate of the route distance between themselves and the object that they had been pointing at. The measure taken was the absolute deviation from the real distance of the path. Any estimation within 5 feet was recorded as an exact match. (A Map of the building with the distance to the objects (route and Euclidean) can be seen in Figure 10)

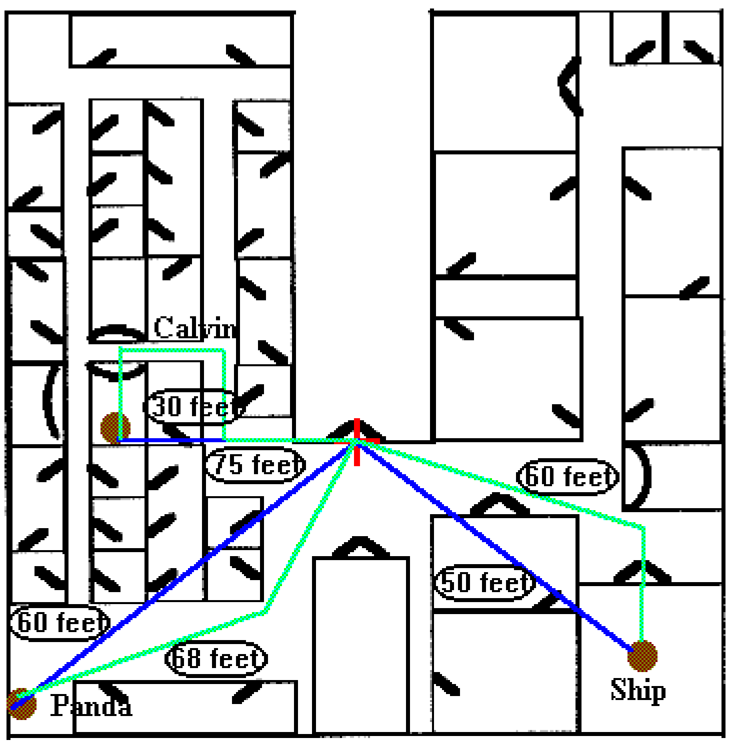

Figure 10 Distance estimation using self as reference: route and Euclidean

The second route distance estimation task was also given to the subjects after they came out of the environment (figure 11). The subjects were given three pairs of locations and asked to estimate the distance between them (Appendix B). Any estimation within 5 feet was recorded as an exact match. If the subjects reported that they do not know where one or both objects were located they were asked to guess the route distance.

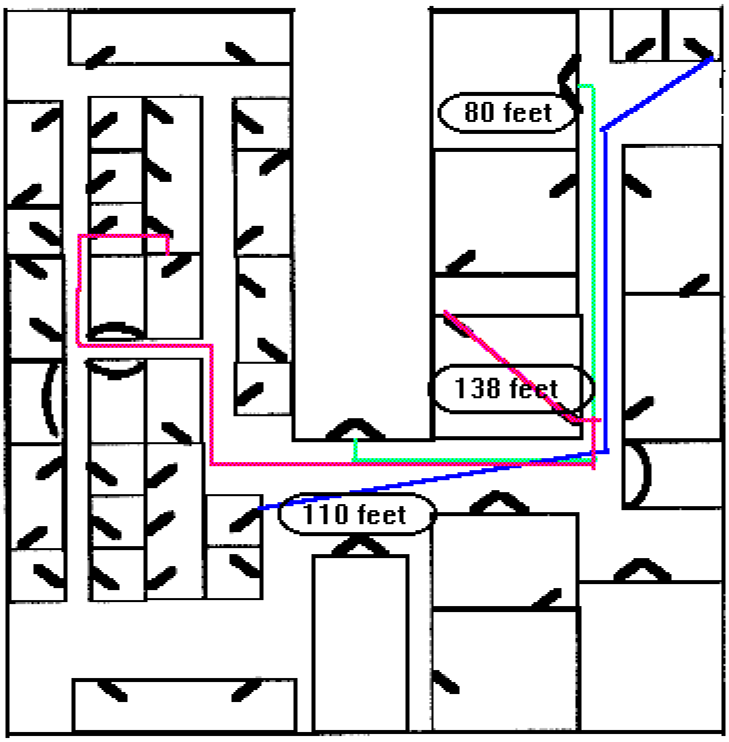

Figure 11 Route distance estimations between 2 objects

Euclidean Distance Estimation Task

There were two types of Euclidean distance estimation tasks given to the subjects. After they had completed the orientation task and given the route distance from themselves to the object, they were asked to give the Euclidean distance from themselves to the object. Any estimation with 5 feet was recorded as an exact match.

The second Euclidean distance estimation task was given to the subjects after they completed the second route distance estimation task (Appendix B). They were asked to give Euclidean distance estimations for three pairs of locations (figure 12). Any estimation within 5 feet was recorded as an exact match. If the subjects reported that they did not know where one or both objects were located they were asked to guess.

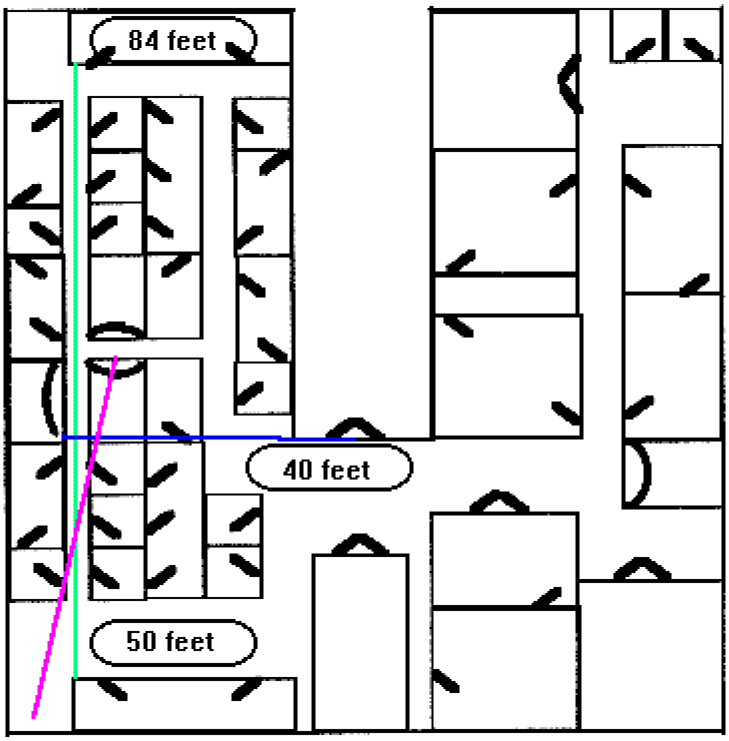

Figure 12 Euclidean distance estimations between 2 objects

<u>*Wayfinding Tasks*</u>

After the subjects had completed all of the tasks listed above they were put back at the entrance of the virtual building for two wayfinding tasks. The paths and maps were removed from the environment, as they were for the orientation task. The first wayfinding task was to go to a specific room taking the most efficient route, and then to return to the entrance door (Appendix C). The path taken (figure 13), the amount of time and the number of errors was recorded. If subjects were not successful in finding the target room after five minutes they were instructed to go onto the next wayfinding task. If they were successful, they had an additional five minutes to return to the entrance door.

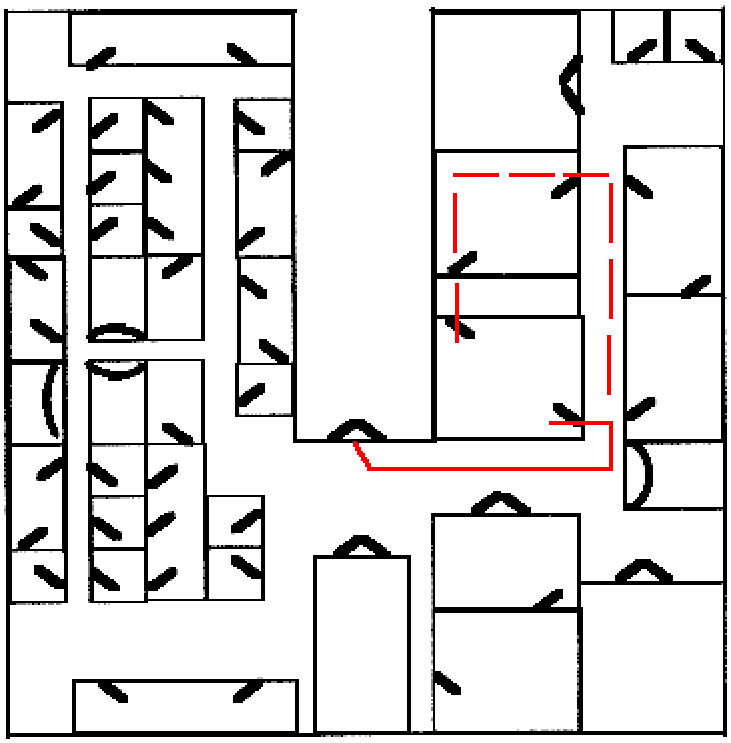

Figure 13 Path for Wayfinding Task 1 (solid line is the most efficient route)

In the second wayfinding task the subjects were placed back at the entrance door. If they had not been successful in returning in the first wayfinding task. They were then asked to locate another room where they were to imagine a friend was located. They were also told that the building was on fire in certain locations and that they could not walk through the fire (Appendix D, figure 14). The two most efficient routes were blocked by fire, so the subjects had to infer a third route to the location. The path taken, the amount of time and the number of errors were recorded. Again, the subjects had five minutes to find the room. If they were successful they then had five minutes to return to the entrance door.

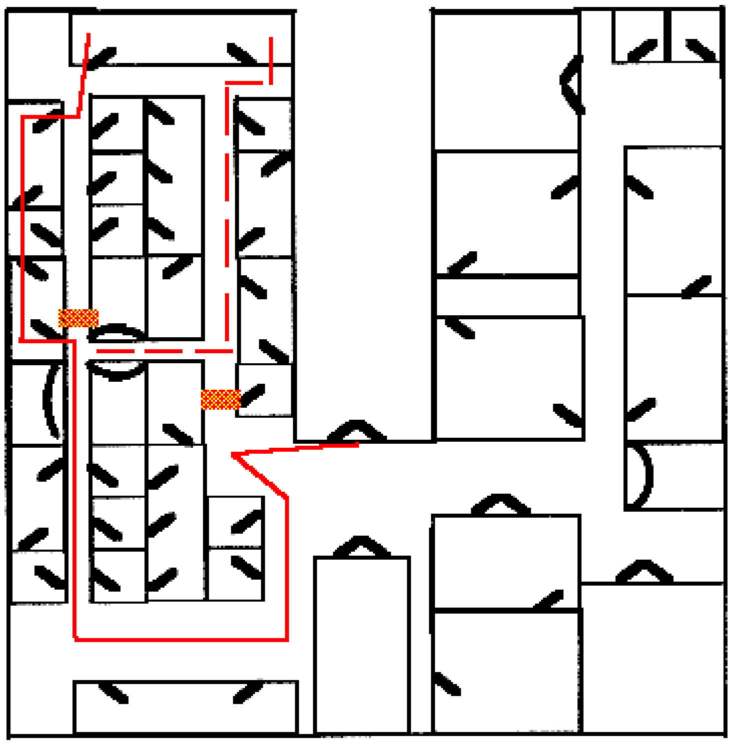

Figure 14 Path for Wayfinding Task 2 (solid line is the most efficient route)

Procedure

The subjects were first given a human subject consent form to sign. Following this they were given a detailed timeline of the experiment (Appendix A). The complete experiment took approximately 2 hours. The timeline for those in the experimental groups was as follows

1. Guilford-Zimmerman Test
2. A detailed description of the condition they were in (Appendix A)
3. Training on how to use the apparatus, and how to move in the virtual world
4. Exploration of the virtual building for one-half hour
5. Orientation Task (in VR)
6. Taken out of VR and asked to give Route distance and Euclidean distances between themselves and objects (Appendix B)

7. Asked for route and Euclidean distances between two pairs of objects. (Appendix B)
8. Put back into the virtual building and asked to do the wayfinding tasks. (Appendix C)

Subjects

There were 65 subjects; five in each of the experimental cells and five in the control cell. Subjects were assigned randomly to each of the conditions. The subjects were all volunteers and were recruited from the University Washington engineering courses, other laboratories, local businesses, and the local chapter of SIG-CHI.

CHAPTER 4

Results and Discussions

Because of time limitations, equipment failure, subject no shows and four subjects reporting simulator sickness; only data from 57 subjects were analyzed in this study. At least four subjects participated in each cell. All statistical data analysis was conducted with SPSS for Windows. The means reported in this thesis are weighted means. This approach produced results by having the means dependent on the number of subjects in each cell, not just the mean of the cell itself.

All of the results reported can be assumed to have met the assumptions for analysis of variance, unless otherwise stated. These assumptions are homogeneity, normality and independence. Homogeneity was measured by using either the Bartlett-Box or Cochran method. Normality was observed by reading histograms and Boxplots of the data.

Spatial Ability Test

The Guilford-Zimmerman has a total of 60 items. Subjects are instructed to complete as many items within a 10 minute time period. The test is scored by subtracting the total of the number wrong divided by 4 from the total number correct. All though subjects were assigned randomly to conditions, an ANOVA based upon the 3 x 2 x 2 (exploration, map before, map during) experimental design for the Guilford-Zimmerman test, results showed a significant difference between those who received a map and those who did not; $F(1,52) = 5.32$, $p < .05$. (Means for all conditions can be seen in Table 2). The means for the map before condition were; map before, M=17.67

(SD=7.23); and no map before, M=23.3 (SD=9.43). Because this variable was being used as a covariate and because of random assignment there was no cause for concern.

There were reliable male-female differences; $F(1,56) = 4.39$, $p < .05$. The means for gender were; male (n=38), M=22.04 s(SD=8.08); and female (n=19), M=17.03 s(SD=7.6). The Guilford Zimmerman reports descriptive statistics for college students, the mean for college aged males is 20, s(SD=10.32) and for college aged females the mean is 12 s(SD=8.67).

Table 2 Means for The Guilford Zimmerman Test

Grand Mean = **21**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB nMB		
Map During	**16**	**23**	**19**	**25**	**15**	**20**	
no Map During	**22**	**28**	**16**	**20**	**14**	**21**	**20**

Procedural Knowledge

The three tasks used to measure procedural knowledge were the directional pointing task (landmark knowledge) and the two route estimation tasks (route knowledge).

<u>*Orientation Task*</u>

A total of 50 experimental subjects were included in the orientation data analysis, as two subjects' data were lost because of a hardware malfunction. The results of the orientation task (angle between pointed location and true location) were analyzed by an ANOVA using the 3 x 2 x 2 experimental design. Means for all conditions are given in Table 3. On the average people who studied the map beforehand were 14 degrees more accurate than those who did not; $F(1,50)$, $p < .05$, map beforehand M=55.83

s(SD=22.08); no map beforehand M=69.88 s(SD=22.12). The control group did not differ from either the map before-no map during exploration group or the no map before-no map during exploration group.

An interaction of the treatments; exploration and map during, also was significant $F(2,50)=3.14$, $p < .05$. The means for this interaction can be found in Table 4.
The means show that for those in the Active Guided condition of exploration, not having a map had detrimental effects. A possible explanation for this result, is that subjects in the active guided group were often observed looking down at the path and not observing their surroundings. If they did not have the map during, while looking down, then they would have little information about where they were in the building. A graph of the interaction can be seen in Figure 15. A total of eight subjects had averages over 90 degrees revealing complete disorientation. Seven of these were in the experimental conditions and one in the control condition.

Table 3 Means for Orientation (average degrees away from targets)

Grand Mean = **61**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	
Map During	**69**	**56**	**45**	**82**	**53**	**71**	
no Map During	**56**	**52**	**64**	**87**	**46**	**68**	**58**

Table 4 Orientation means for Explore by Map During Interaction

	Self Exploration	Active Guidance	Passive Guidance
Map During	**62.9**	**64.2**	**62.3**
No Map During	**54.8**	**75.4**	**57.6**

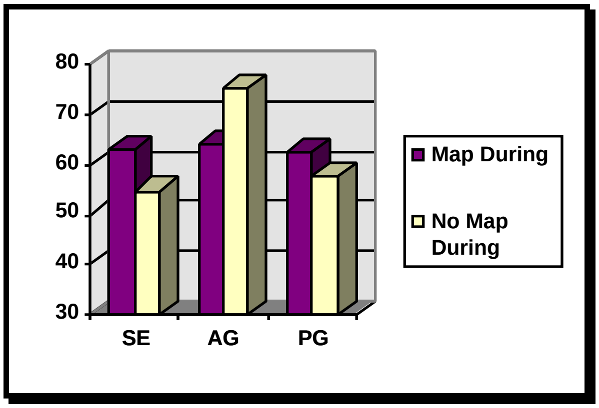

Figure 15 Orientation Interaction of Exploration and Map During

Route Estimation (for objects used in orientation task)

All 52 experimental subjects estimated distances from the entrance door to the same three landmarks (ship, picture of Calvin and picture of the panda bear). The average of the absolute differences between the objects was analyzed using the 3 x 2 x 2 between subject experimental design. The analysis was not successful as the assumptions for normality and homogeneity were violated as one subject in the Active Guided, No Map Before, No Map During condition was 3 standard deviations above the norm. When this subject's data was removed from the data set, all assumptions were met. An ANOVA of the revised data set showed that performance was marginally better (although not significant) for those who received a map before they entered the environment than those who did not: $F(f1,38) = 3.46$, $p < .07$; M(map before)= 19.8, s(SD=10.97), M(no map before)= 24.73, s(SD=9.7), means for all conditions can be seen in Table 5. In addition, the control subjects' performance was better than those who did not receive a map before and during; $t6.8=2.56$, $p < .05$, M(control)=13.66, M(no map before and during)=20.35.

Table 5 Route Estimation Means (Self as Reference: absolute distance from true distance in feet)

Grand Mean = **21**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	
Map During	**10**	**19**	**23**	**26**	**19**	**26**	
no Map During	**13**	**30**	**27**	**20**	**22**	**19**	**13**

Route Estimation (between two landmarks)

All 52 experimental subjects gave route distance estimations between the following landmarks; entrance door and the tea room entrance door, between the two men's bathrooms, and between the black monolith and the clock. The results (absolute distances in feet, from the true distances) were analyzed using the 3 x 2 x 2 experimental design. The results were significant for the map before condition $F(1,39)=11.01$, $p < .05$; map before M=41.73 s(SD=20.7), no map before M=57.92 s(SD=20.4). The main effect of exploration was also significant, $F(2,39)=3.21$, $p<.05$; self exploration M=57.98 s(SD=23.43), active guided M=48.18 s(SD=22.58), and passive guided M=43.25 s(SD=18.17). The means for all conditions can be seen in Table 6. The finding that self exploration engenders less accuracy than that of the guided groups was surprising, as it conflicts with what the literature suggests. For example, Passini (1982), stated that guides may decrease performance because fewer decisions are made than when one self explores.

An interesting interaction was also revealed for the map before and map during; $F(1,39)=3.89$, $p < .05$. The means are given in Table 7 and shown graphically in Figure 16. The means show that people do their worst when they never have a map for route distances. Contrasts for the route estimations between two landmarks proved significant. The first contrast looked at those who studied a map and explored the environment versus those who only studied the map but had no map in exploration; $t_{10.7}=3.54$, $p<.05$; map before with no map during M=39.38, control M=17.1. The second contrast compared those who explored the environment with maps neither before nor during, and the control subjects who studied the map but had no exploration; $t_{10.8}=6.45$, $p<.05$, no maps M=66.13, control M=17.1. This second contrast again shows that secondary survey knowledge produced more accurate estimations than those with procedural knowledge. The control contrasts clearly showed that exploration of the virtual environment caused a deterioration in estimation performance.

Table 6 Route Estimation Means (between 2 objects)

Grand Mean = **46**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	
Map During	**57**	**57**	**39**	**46**	**37**	**44**	
no Map During	**50**	**66**	**29**	**77**	**38**	**54**	**17**

Table 7 Route means for Interaction of Map Before by Map During

	Map Before	No Map Before
Map During	44.8	41.8
No Map During	47.3	66.3

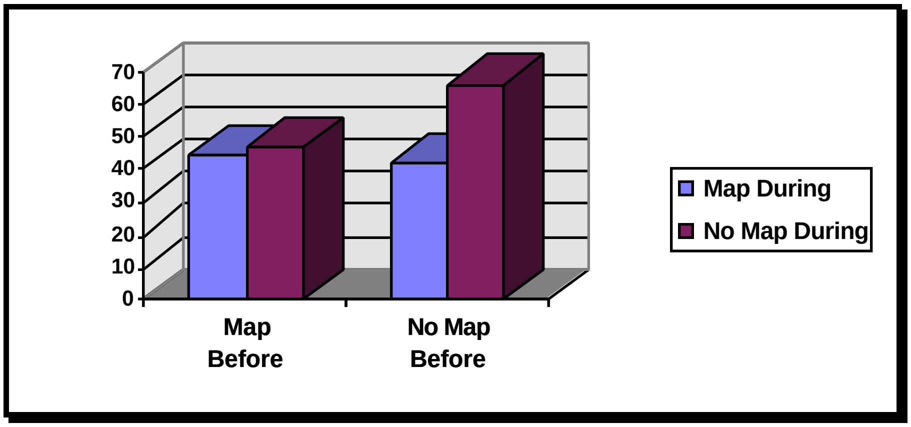

Figure 16 Route Est. Interaction for Map Before by Map During

Survey Knowledge

The Euclidean distance estimation tasks were used to measure survey knowledge. In the first task subjects used themselves as a reference point to give straight line distances to the landmarks they had previously pointed at and given route estimations to. The second task was giving straight line distance estimations between two objects. The hypothesis was that those who had a map to study beforehand would be better at the distance estimations than those who did not. It was also hypothesized that the control group would do better than those who did not have a map at all because of the benefits of having secondary survey knowledge.

The ANOVA results for the first task did not reveal any significant differences between the experimental conditions or contrasts with the control condition (means are given in Table 8.) The ANOVA for the second survey estimation task did show a benefit from studying the map before going into the virtual environment; $F_{1,39}=7.30$, $p < .01$, map before M=16.86 s(SD=11.8) and the no map before M=28.90 s(SD=10.0). Means for all conditions are given in Table 9. The first contrast comparing the control group to those who explored the environment and did have the map to study before was not significant. The second contrast indicated that the control group was superior in judging straight line distances than those who did not have a map to study did show significance ($t_{8.0}=2.531$, $p<.05$). The mean for the control group was M=11.93 s(SD=9.16) and for contrasting groups M=24.80 s(SD=10.1).

Table 8 Straight Line Distance Estimations (Self as Reference: absolute distance from true distance in feet)

Grand Mean = **18**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	
Map During	**11**	**20**	**17**	**26**	**18**	**21**	
no Map During	**16**	**19**	**19**	**15**	**36**	**19**	**14**

Table 9 Straight Line Distance Estimations (Between 2 Objects: absolute distance from true distance in feet)

Grand Mean = **19**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	
Map During	**15**	**26**	**22**	**17**	**15**	**25**	
no Map During	**16**	**29**	**20**	**21**	**10**	**23**	**12**

These results show that having a map before entering the virtual environment was beneficial and that exploring the virtual environment did not add to performance beyond the information gained from the map.

Discussion of Procedural and Survey Knowledge

All three measures (orientation, route estimation, Euclidean estimations) shows that having a map before entering the virtual environment improves performance. In no case did the experience of the virtual environment provide performance (hence an accurate spatial model) than did map study alone. By some measures the virtual environment experience actually degraded performance. This unexpected result will be discussed later. A cursory comparison of means for the real number (not absolute distances) distance between the estimated distance and the actual distance from the target location for all the groups was performed, and again the control group was closer to the real distances than the experimental groups. The experimental groups were inconsistent across the four distance estimation task as to which group underestimated the distance the most or least . All groups underestimated the true distance as has been found in previous research in VR (Waller, 1994).

Wayfinding

Wayfinding is possibly the most valid way to assess navigational knowledge. The first wayfinding task was to find the classroom where subjects had seen two whiteboards on the wall saying “I will not talk in class” (figure 17). The guided tours subjects saw this classroom last. Figure 13 shows the routes. For those subjects who studied the map beforehand, the classrooms were not differentiated on the map. When the subjects were asked if they remembered seeing such a room, all 52 experimental subjects answered affirmatively. Since the control subjects did not explore the environment, they did not before hand the location of the target classroom.

Figure 17 Wayfinding 1 Target Room

The wayfinding task was scored using the paths shown in Figure 13. A maximum of four points was possible. The first point was given if the subject turned left immediately. The second point was given if the subject then took the next left without detouring. Two points were given if the subject then entered the door on the left (target room) without detour. One point was given if the subject detoured and went into another classroom but eventually came back to the target door from the hallway. One point was also awarded if the subject entered the target room from the adjoining small room. The routes were monitored and timed while in progress. When the subject recognized that they were in the correct room the time was noted. The subject was then asked to return to the entrance door. Up to four points were also awarded for the return trip; two for exiting the through the hallway door, one for turning right and one for stopping at the entrance/exit door. Time and route taken were also monitored.

All subjects participated in both wayfinding tasks. In the first wayfinding task 40 of the 52 subjects turned in the proper direction (left). Only 19 subjects found the target room within the 5 minute time limit. Of those 19 subjects 16 returned to the entrance door within the 5 additional minutes. Only one subject performed flawlessly.

The mean performance for the first wayfinding task are shown in Table 10. An ANOVA showed that those subjects who had a map before they entered the environment for the exploration period performed better, $F_{1,39} = 8.43$, $p < .05$; M(map before group) 2.0 and the no map before group M=1.3. Thirteen of the nineteen subjects who found the room had seen the map before, the other six had not. A marginal trend was found for those in the map during condition; $F_{1,39} = 3.71$, $p < .07$; Mean for map during M=1.3, Mean for no map during M=2.0. This suggests that the map during condition may have interfered with wayfinding. Twelve of the thirteen subjects in the map before condition returned to the entrance/exit door, and four of the six in the no map before condition returned. The scores of subjects who had a map before were significantly higher on the return trip than those who did not; $F_{1,39} = 4.26$, $p < .05$. The mean for map before was M=1.5 and the mean for no map before was M=.84. Four of the 6 subjects in the no map before condition who found the room, did not have a map during exploration. The same 4 subjects found their way back to the starting point. The control group performed well, as three out of the five subjects found the target room, even though it was not specifically designated on the map. Two of the three control subjects also successfully returned to the entrance/exit door. All of the subjects took the initial left turn. Again the control subjects performed as well as or better than each of the other cells in the experimental design. There were no differences in the contrasts between the controls and those in the virtual environment experimental conditions.

The average time to find the target room was 164 seconds and the average time it took the subject to return to the entrance/exit door was 47 seconds. This time difference is significant $t_{16} = 7.47$, $p<.001$(paired t test). Clearly those who found the target room knew how to get back to the starting point. There were no significant time differences between the exploration conditions and the control group.

Table 10 Means for finding the target room in Wayfinding Task 1 (four points possible)

Grand Mean = **1.67**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB nMB		
Map During	**2**	**.6**	**2.4**	**.75**	**1.2**	**1.2**	
no Map During	**2**	**2.5**	**2.5**	**1.2**	**2**	**1.5**	**1.8**

The ANOVA completed for the points scores in the first wayfinding task showed that the covariate was significant for both finding the target room, $F_{1,39}=4.13$, $p < .05$ and the return phase also; $F_{1,39}=4.20$, $p < .05$. The effects size for (ω^2) for finding the target room was .096 and for returning was .097. These results are in line with Infield's research showing that the Guilford-Zimmerman can be used as a predictor of navigation performance on land and now can be used in Virtual Environments.

The second wayfinding task presented special problems to the subject because the two main routes to the target room were blocked with fire walls (Figure 18). The second target room was a laboratory that had one table (Figure 19). The two laboratories in the building were specified on the map as having one table or two. Subjects that were in the experimental conditions were reminded that there was a large double helix (DNA molecule) on top of the table. All experimental subjects and control subjects said they were familiar with the room or at least the specifications of the room.

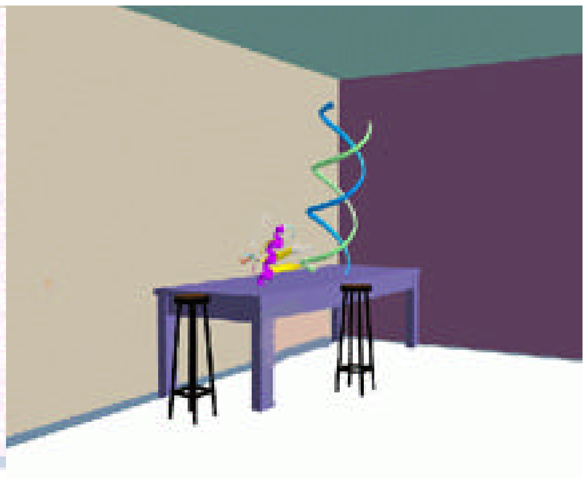

Figure 18 A Fire wall in Wayfinding 2 **Figure 19 Wayfinding 2 Target Room**

The second wayfinding task was scored with a maximum score of nine points (Figure 14). The first point was given for starting in the correct direction (right). The second point was given for moving towards the first hallway to the right. This hallway was the shortest route to the laboratory but was blocked by fire. The fire could not be seen till the hallway was entered. The third point was scored if the next move was to go along the area near the bathrooms towards the other laboratory. If the subject then turned right and went down to the next hallway another point was earned. Many subjects went into the laboratory with the two tables, and points were not given for this maneuver. The fourth point was awarded if the subject turned right to go down the second hallway. Many subjects were observed being apprehensive about this move, as they could see another fire wall down the hall, which would block their way, if they were to try to continue all the way down the hall (figure 18). The fifth point was given if they continued walking down the hall towards the fire wall. When they neared the fire wall a decision had to be made to either turn right, left or turn around and go back. Two points were given if the subject went left into the executive office. An additional point was given when the subject exited either the secretary's or the far executive office door. If the subject then turned left and entered the lab door straight a head of them and into the target room the additional two points were given.

A half point was given if they went right down the bisecting hallway instead of turning left into the first executive office. If the subject then turned left and walked towards the lab with detouring into the offices on the right side of hallway another half point was given. If the subject then turned right and then left into the lab door they were given one point. The total points that could be awarded for taking this tour were 6 points. One subject in the experimental condition completed the nine point tour flawlessly, as did one subject in the control condition. Four experimental subjects and one control subject completed the return trip using the shortest route.

Five subjects initially turned left at the entrance door instead of right. Two of the five had turned incorrectly on the first wayfinding task. The results that more subjects turned in the correct direction for the second task are in line with having previous experience in the building during the first wayfinding task. During the first wayfinding task subjects thoroughly explored the left wing of the building and possibly remembered that the lab was not in that wing. Twenty nine of the 57 subjects (including control subjects) entered the laboratory where there were the two tables. Many of the subjects commented that they knew the task would not be that easy but they checked it out anyway. Twenty-two of the 52 experimental subjects found the target room within the five minute time limit. (See mean scores for Wayfinding 2 Task in Table 11) Of the 22 successful subjects, 15 found there way back to the entrance/exit door. There were no significant differences across the experimental conditions. The contrast between the control and those who did not have access to any maps was significant, $t_{6.3} = 2.68$, $p < .05$. The average time it took a subject to find the target room if successful was 200 seconds. The average time it took the subject to return was 129 seconds. Using the paired t-test the time difference was shown to be significant: $t_{14}=8.13$, $p<.001$. There were no significant time differences between the exploration groups and the control group.

Table 11 Means for finding the target room in Wayfinding Task 2 (nine points possible)

Grand Mean = **3.88**	Self Exploration		Active Guided		Passive Guided		Control
(Map/noMap Before)	MB	nMB	MB	nMB	MB	nMB	
Map During	**4.25**	**3**	**3.8**	**4.25**	**4.2**	**3**	
no Map During	**4.25**	**2.5**	**2.75**	**3**	**4.8**	**3.75**	**6.2**

Many of the subjects made insightful comments that highlight the four steps involved in wayfinding. The first step in wayfinding is orientation: Knowing where one is in respect to objects nearby and one’s relative position in the world. Comments made by the subjects included the following: “I miss the lines for orienting myself. I don’t think I was careful enough to pick out a landmark before I turned around”, “Where’s my map? You took away the lines too!”, “It’s hard without the lines.”

The second step in wayfinding was deciding which route would lead to their destination. The task specified that the shortest route be used. Comments related to this step were most prevalent in the second wayfinding task when subjects attempted to turn right down the first hallway and were blocked by fire. Specific comments were, “Oh sure! block the easiest route,” and “You took away the direct route.”

The third step of route monitoring generated the most comments, both positive and negative. Positive comments included “Well that’s a classroom, so I must be in the classroom neighborhood,” and in the second wayfinding task as one subject turned left into the executive room and then quickly moved through the three offices stated “Oh here we go to the lab.” The negative comments were made when some subjects ventured over to the right wing during the first wayfinding task and recognized that they were not in the correct area for the classrooms: “What am I doing over here”, “I am going the wrong way”, “What is going on? I’m in the total wrong part of the building?” Many just stated “I’m in the wrong wing.” The most insightful comments for the second wayfinding task were “Where did all these rooms come from?”, and “Oh, the lab has two doors.” There were no specific comments about reaching the destination, but subjects groaned when asked to return to the entrance/exit door.

The comments and behaviors of these subjects clearly show that Regian’s (1991) random walk is not an appropriate control. Only five subjects in the first wayfinding task reentered a room in which they had previously been. Six subjects entered the same room twice, unintentionally, in the second wayfinding task. Four of these six subjects kept going back into the lab with the two tables. Many subjects traversed hallways more than necessary while trying to find a target room, but few subjects traversed the same hallway more than twice than needed. Subjects, even when lost, would not backtrack without purpose.

Observations of the Conditions During Exploration

Each of the three exploration conditions elicited unique subject behaviors. Self-exploration was the most interesting to watch. Some subjects were curious and wanted to check every room and every object. They physically squatted to look under tables and desks. Other subjects would wander the hallways, look at the pictures, go to the open-faced rooms, and then finally start entering the rooms through the doorways. A few subjects who studied the map before entering the building seemed to have a destination in mind and what they wanted to see first. Subjects could be grouped into those who were curious versus those who were hesitant or unsure of where to go.

Subjects in the active guided group seemed to have the most difficulty. They were told that they should stay near the path but that they did not have to stay directly on it. Many subjects looked straight down instead of watching what was around them so as to stay on the path. Similarly, when they came to an area where the line was straight ahead for some distance, subjects would use the turbo button to zoom down the line without noticing what was around them.

The passive guided group performed very well, considering there were hardware and software difficulties that required them to stay near the head-tracking receiver when going through doorways. These subjects often leaned backwards to see what was in some of the rooms that they did not enter. A few subjects verbally reported that they wished the tour would stop so they could better view things around them.

It was difficult for the experimenter to discern if subjects were attending to the map unless they specifically reported something about the map. Most subjects commented that they would prefer an arrow (rather than just a crosshair) to indicate both position and orientation.

CHAPTER 5

Conclusions and Directions

This study provided a surprising, counter-intuitive and perhaps important results. People who explored a virtual environment were compared to a control group who were given a map of the same environment but no direct experience of it. Subsequently, all subjects were asked to perform navigational tasks in the same virtual environment. By all measures used, people who had the virtual experience either performed equivalently or worse than the control group. This result certainly serves as a caution to enthusiasts (e.g. Rheingold, 1991) who appear to believe that virtual environments may be superior training environments.

But, there maybe explanations for the poor performance by those who explored the virtual environments. One possibility is that the subjects simply did not have enough time in the virtual environment. Subjects in this experiment experienced a virtual environment for 30 minutes. Navigation studies in the real world have shown that egocentric exploration of an environment, results in more accurate orientation and route estimations than those who have only seen a map of the area. This is opposite to the findings of this study. However, real world studies often contrasted map study to weeks or months of primary experience. Further, in at least some cases people can fail to gain Euclidean knowledge of an environment even after years of experience (Moeser, 1988). It is likely that repeated exposures to a virtual environment will increase subject proficiency to that of a control group (with 5 minutes of map study), but at what cost.

A more interesting possibility is that the VR experience was a distraction; not because VR is inherently a poor training medium, but because is was simply unfamiliar.

The majority of subjects (50 or 57) were novices to VR, and therefore the interface problems of the hardware may have had a negative effect. A recent study by the University of Wales (1995) , where subjects were exposed to a virtual environment replicating a real environment, stated that subjects took four to six hours for there performance to equal subjects trained in the real environment.

Another explanation is that the virtual environment training was compromised by the intrusiveness of the VR interface. Subjects could not behave naturally. Removing all artifactual differences in the interface would approach an experience similar to that seen in the holodeck of the TV science fiction show Star Trek. Presumably training in a holodeck environment would be equivalent to training in a real environment but with the advantage of built in safeguards. But rather than dreaming of this fictional environment a more relevant question is how can we use the virtual interfaces the can build in the next ten years. As of today, we know that many factors can hinder the virtual experience, such as lag time between the user’s action and the system’s response, the weight, resolution, and field-of-view of an HMD, the weight of a wand and the unnaturalness of using the hand or button presses to initiate walking. All of these engineering and user-interface design problems are currently being acted upon,but it is unknown at what point they have to reach ,so that VR will not interfere with a user’s natural behavior.

This study also examined the use of different tools and cues during exploration. The results indicate that in some cases a map during exploration may have interfered with learning. These results are consistent with the argument that any tool that attracts attention to itself may interfere with the learning it is supposed to facilitate. Clearly, we need, virtual environment tools that concentrate attention upon the development of an appropriate Euclidean representation. For instance, it might help to modify the map to show position and orientation. An intriguing tool has been demonstrated by Randy Pausch (Stoakley, Conway and Pausch, 1995) that may improve navigational awareness and wayfinding in virtual environments. This tool produces 3-D miniature image of the virtual environment occupied by a user, which is held in a virtual hand. With the other hand the user holds an image of a body (representing the user). As the body image is positioned in the miniature environment the user is passively transported to the new spot. At present the tool transports the user through walls causing some disorientation, but with some modifications the shortest route through virtual doorways could be achieved.

The paths used in these experiments could also be modified. One possibility is to elevate the path above the floor. In this experiment the path was placed on the floor as it would appear in a real world environment. In the active guided condition this placement caused the participants to look down constantly, making it difficult to scan the environment around them. This was not the case for those who were passively guided as they did not have to constantly monitor the line. With so many options for tools and cues that can be implemented in virtual environments, the challenge is to find a tool that equals or surpasses performance in the real world for navigational awareness and wayfinding.

The most important conclusion of this thesis is that there are differences or artifacts between virtual and real environments that affect performance in simple navigation and wayfinding tasks. This begs the question of what these differences and how might the quality of virtual interface hardware and environments be changed to improve the propensity of virtual technologies to train real world tasks. Further research is needed to ascertain these artifacts. The navigation and wayfinding task, and the metrics presented in this thesis may be useful tools for assessing the goodness of virtual interfaces and determining these artifacts. If virtual reality is to be used effectively for training spatial awareness in real world environments, these issues must ultimately be addressed and resolved.

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APPENDIX A: INSTRUCTIONS AND EXPERIMENTAL TIMELINE

Welcome to the Human Interface Technology Laboratory (HITLab). For the next 60 to 90 minutes you will be participating in a research study examining what is the most effective manner to expose someone to a new environment. For this study you will be exploring a mythical building in Virtual Reality (VR). The building is U shaped and measures 100 feet by 100 feet. The following is a timeline of what you will be asked to do.

1. For the first 15 minutes you will be asked to take a test that examines spatial ability. The test will **not** determine whether you continue for the rest of the study.

2. (Subjects who received a Map Before Going into the Environment) You will be given a map of the virtual building to study for 5 minutes.

3. You will then be taken to the entrance of the building. (Free Exportation) For the next half hour you will be free to explore the building in any manner you choose. (Active Guided) For the next half hour you will be able to explore the building by following the path laid out for you. You will start by following the green line at the entrance door. It is very important that you follow this path. If the path does not go into a room please do **not** enter that room. You are free to look in the doorways though. (Passive Guided) For the next half hour you will be guided through the building. This will be similar to being a passenger in a car but with some differences. When you are moving around a corner you will need to turn you head to the new direction. You are free to look in any direction you want but you will be moving forward at all times. (Self-Explore and Active Guided) You will not be able to go through the walls but the objects you see, you will be able to. It is not encouraged that you go through the objects, but you have the ability to. (Map During Subjects) You will notice a map of the world in the lower right corner. There is a red marker on the map that will show your position in the building at all times. (All Subjects) The time will be given to you in 5 minute increments. After a half hour the exploration segment of this study will end.

4. You will be asked to do some tasks in the virtual building, (Directional Pointing Task) then you will be taken out.

5. A questionnaire will then be given to you for you to answer (Distance Estimation Tasks).

6. Following the questionnaire you will be asked to go back into the virtual building and do some additional tasks (Wayfinding Tasks).

7. If being in the virtual environment affects you negatively, close your eyes and the headset will be removed. If you have any questions, please ask them before you go into the virtual environment or after you have come out. You are free to make any comments you want during the exploration period. Thank you for your participation.

APPENDIX B: ESTIMATION TASKS

Answer the following questions as accurately as you can. The building is U shaped and measures 100 feet by 100 feet. If you cannot remember where the room or object is being asked about, please give it your best guess.

Imagine yourself walking from the first location to the second location.

1a. What is the distance of the shortest route between you standing at the entrance door and ship (in feet)? ______________________

1b. What is the distance of the shortest route between you standing at the entrance door and the picture of Calvin (in feet)? ______________________

1c. What is the distance of the shortest route between you standing at the entrance door and the picture of the Panda bear (in feet)? ______________________

2a. What is the distance of the shortest route between the entrance door and the tea room entrance door (in feet)? ______________________

2b. What is the distance of the shortest route between of the two men's bathrooms (door to door) in feet? ______________________

2c. What is the distance of the shortest route between the room with pictures of the earth, Saturn, and the black monolith and room with the clock face that reads three o'clock (door to door in feet)? ______________________

Imagine yourself flying in a straight line from the first location to the second.

3a. What is the straight line distance between you standing at the entrance door and ship (in feet)? ______________________

3b. What is the straight line distance between you standing at the entrance door and the picture of Calvin (in feet)? ______________________

3c. What is the straight line distance between you standing at the entrance door and the picture of the Panda bear (in feet)? ______________________

4a. What is the distance between the two laboratories (door to door in feet)?

____

4b. What is the distance between the entrance door and the door to the room with the colored marble columns (in feet)? ________________________

4c. What is the distance between the wall with picture of the tiger and entrance to the room with a picture of Calvin and playing blocks (in feet)? ________________________

APPENDIX C: WAYFINDING TASKS

For the next 2 tasks you will be placed back at the entrance door of the virtual building. From there you will be asked to travel to a particular location in the building. For this task it is requested that you find the location using the shortest route possible. You will have 5 minutes to find the location. When you find the location, you will have 5 additional minutes to return to the entrance door, again using the shortest possible path.

For the second task, imagine the building is on fire in certain areas and you need to rescue a friend. You need to find the location of your friend within 5 minutes. You are not allowed to walk through fire. Take the shortest path to the location and back.