Abstract

BARLOW, STEVEN TODD. Spatial Knowledge Acquired Through Navigation In A Large-Scale Virtual Environment. (Under the direction of Sharolyn Converse.)

The effects of changes in elevation, route distance, route complexity, and non-spatial information on memory for a virtual environment were investigated. Thirty college students learned the layout of a two-story virtual environment through a series of navigation tasks. Participants were required to learn the route from a starting point to each of 14 rooms in the environment. After completing six blocks of learning trials, the participants estimated route distances and directions, completed a priming task in which they identified the floor that each room was on, and navigated novel routes that were not traversed in the learning trials. The results indicated that the elevation, route distance, and route complexity, affected both learning and memory for the environment. In contrast, non-spatial information had no effect on memory for room location or the layout of the virtual environment.

SPATIAL KNOWLEDGE ACQUIRED THROUGH NAVIGATION IN A LARGE-SCALE VIRTUAL ENVIRONMENT

by
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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

PSYCHOLOGY

Raleigh

1999

APPROVED BY:

Chair of Advisory Committee

Biography

I've always been fascinated by maps. The first map I remember clearly was framed and mounted on our townhouse wall in Toronto. It was a map of the United States. Each state was a different colored piece of felt. My grandmother made it. It was big move from Alabama to Toronto. I think she wanted us to remember where we were from. Many of the states had small trinkets attached to them. The trinkets represented a theme commonly associated with that state. Nevada had a pair of dice attached to it. Hawaii had a pineapple. Mississippi had cotton. Not every state had its own theme. I don't remember anything about New Hampshire, Vermont, Maine, and those other small cold places.

As a kid, I remember talking with my dad about the location of this or that. Invariably, he would use cardinal directions to describe a location. "It's about 300 yards east of the north end of the park." Although I had no idea what he was talking about I would nod my head knowingly and try not to let what he said confuse me. Since then I've found myself using cardinal directions. I've also found myself looking into people's eyes and seeing that same empty look my dad probably saw in my eyes. Like me, they are probably thinking "I'm not Lewis and I'm not Clark. Don't bother with your east-west gibberish. Give me left, right, up and down."

Ever since I've been responsible for getting myself or others somewhere, I've spent an inordinate (according to my wife) amount of time studying maps. I don't think it started immediately upon getting my driver's license though. I remember feeling fairly confident that I knew where everything was that I needed to get to, when I first started driving. I had been playing soccer for 9 years by the time I got my license and was fairly adept, I thought, at remembering the routes to soccer fields all over the Washington DC metropolitan area. By extension, I thought I knew how to get to almost anything I had visited previously- "one trial learning" you might say. Much to my chagrin, the first time I was behind the wheel on a date, I was driving to the movies when I suddenly realized I had no idea where I was going. I had headed off in the "right" direction only to find myself in a unfamiliar area with no recognizable landmarks. I stopped the car and called my father for directions. [Note to all male readers: I swear this is the last time I ever stopped and asked somebody for directions.]

Given the trouble I found myself in on that first date, it should come as no surprise that I consider my sense of direction far above average. When I first met my wife, she was selling car phones. They were the latest toy for people with $1200 to burn. Her job required her to drive all over the place to meet people at their offices, homes, restaurants, and wherever they found convenient. More than once she called me and said "I'm trying to get to <someplace> and I'm at <nowhere near where she should be>. What do I do?" Then I would give her step-by-step instructions from her origin to her destination. I don't remember ever failing to get her where she wanted to go. However, that may be as much an artifact of my selective memory as it is a testament to my knowledge of the our hometown. By the way, she will still sell you a telephone for $1200 and you don't have to commit to a service plan.

Like most couples, we've had our differences over the disparity in our ability and interest in navigation skills and map reading. Before I became a professional psychologist, I was less aware of individual differences in people's abilities. I assumed that everyone should be able to read a map. Of course, now that I'm a trained observer and interpreter of human behavior I've come to this conclusion: "People are different. Not everybody is like me. Not everybody wants to be like me." In light of our differences and our desire to remain married and happy that we are married, I no longer ask her to read maps while I'm driving. If we need directions somewhere, we write them out before we start driving.

When I enrolled at State, I had no idea what topic I might select for my dissertation. I had toyed with the idea of maps and navigation for my Master's thesis. Intelligent transportation systems were beginning to get funding. In-vehicle navigation systems were some of the first components to be investigated. Fortunately, a very helpful faculty member (Thanks Dr. Boles!) steered me away from it. He pointed out that none of the faculty had any experience in the area. If I chose that topic, I would be completely on my own. After conferring with two other people familiar with the this sort of thing (Thanks Mom and Dad!) I agreed.

By the time I finished my Ph.D. coursework, I still had no idea what I wanted to study. I had, by that time, begun playing a very addictive computer game. I wasted many, many hours in front of my computer doing "research" on navigation in virtual environments. At some point, it dawned on me that I could use my addiction to my advantage. Even though I had already decided on the methodology and had a hazy idea about the independent and dependent variables, I had to convince my committee that doing research on virtual environments was necessary and meaningful. Doing research because it's fun is reserved for people who've already earned their Ph.D. After reading a few reviews of research in the area, I decided that involving maps in my dissertation opened up an enormous can of worms. In a cunningly strategic decision, I opted for the study of navigation in virtual environments without reference to maps. By excluding maps from the navigation task, I made my dissertation unique and limited the amount of research I had to include in my literature review. Thus my dissertation was born.

This document is the final, presentable, officially-sanctioned version of my research. In no way does it represent the amount of work, worry, sleep deprivation, aggravation with computers, cursing at the developers of free software, and time away from my family that is an innate part of completing a dissertation. While working on a dissertation may, at times, seem like a solitary task, few people are solely responsible for their accomplishments. I've found the faculty in the Psychology Department at State to be interesting, committed to high quality research, and supportive of almost everything I've done. Most importantly, my family has worked around my schedule for the past few years whenever I my dissertation called me. Though they were not be able to help me think, analyze, or write, they were, without question, invaluable to me.

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Introduction

The research described in this document is designed to explore knowledge about large-scale virtual environments gained through direct navigation in the environment. Large-scale space cannot be viewed, in whole, from a single vantage point. A large-scale space requires spatial and temporal summation because a person must move through the environment in order to experience it. Direct navigation is first-person movement through an environment. Movement and direction of movement are under the control of the person in the environment. The virtual environment, in this research, was presented and experienced through a desk top display and control.

This research examined the effects of four independent variables on navigation in a virtual environment and memory for the environment. The independent variables are: route length, route complexity, changes in elevation, and semantic grouping. The first three variables are objective environmental characteristics. Each has been shown to influence cognitive representations of real-world environments. The fourth variable, semantic grouping, is a subjective characteristic of the environment. It is influenced by objective environmental characteristics and influences encoding and recall of spatial relationships in the environment.

While previous research has considered the effects of one or more of these variables, this research is the first to combine the four in one study. Significant work has been done on the effect of route length and complexity on cognitive representations of the environment. However, few studies have controlled the learning of the environment by manipulating route length and complexity during initial exposure to the environment. Very little research exists that looks at the effect of changes in elevation on the development of cognitive maps. None of those studies systematically varied route-elevation change for environments learned through direct navigation. Investigations of the effects of semantic grouping have been pursued independent of the research on environmental characteristics. The research described here was done to determine whether there is an interaction between these two types of variables.

The research also has practical importance. In the area of intelligent transportation systems, an understanding of the development of cognitive maps can be useful in designing driver-training procedures, route-planning systems, and route-guidance systems. The same knowledge can be applied to other domains in which navigation and understanding of the environment are critical, e.g., aircraft navigation, ship navigation, and off-road navigation. As virtual environments become less expensive and more prevalent, the relationship between navigation in the real-world and virtual environments must be understood. While the environment used in this study is not an immersive environment like those used in military crewstation or aerospace research, the same technology is being used by the Marines as a team-training tool.

This document is comprised of six major sections. The first section (this section) describes the purpose of the research and briefly reviews the concept of cognitive maps. The second section reviews the relevant research regarding the four independent variables described previously. The third section describes the hypotheses, experimental design, the independent and dependent variables, and the experimental procedures. The fifth section describes the analysis of the data. The sixth section interprets the analysis and discusses the findings.

Overview of Cognitive Maps

The term “cognitive map” was introduced by Tolman (1948) to explain performance of rats while they navigated a maze. The rats behaved as if they had developed a survey representation or “map” of the maze.

The term “cognitive map” is a metaphor for the structure of environmental knowledge and the method of its use (Downs, 1981). It is an inappropriate metaphor because environmental knowledge is not stored in a unitary spatial format (Montello, 1992). It is the misinterpretation of Tolman’s work that has caused problems for the metaphor (Downs, 1981). Tolman was trying to describe a process- not a product. At no point did Tolman specify which properties of the mental map are equivalent to a cartographic map. Unfortunately, many of the inferences people draw about cognitive maps are based on their experience with cartographic maps. However, a cartographic map cannot be used to explain a cognitive map. Neither the cartographic map nor the cognitive map is the real-world. To say that a mental map is like a cartographic map is to misunderstand what a cartographic map represents. It also provides no explanation of the structure and processes of spatial cognition.

The following commonalities can be found across most research on cognitive maps:

- A cognitive map is a construct used to describe knowledge of large-scale environments.
- Cognitive mapping is the mental process through which people come to form and use

knowledge about the spatial aspects of the world (Downs & Stea, 1977).

- This process translates spatial information into a representation within memory that will be useful at a later date. Object identification, location, and temporal qualities are acquired, organized, and stored for future use.
- Cognitive mapping is a purposeful and goal-directed activity.

Still, there is no dominant viewpoint in the study of memory for large-scale environments (McGuinness, 1992). Research findings differ because of the environments in which the data are collected, the means of learning about the environment, and the measures used to assess knowledge of the environment. Researchers from a variety of fields have contributed to the research in this domain. This diversity in backgrounds is evident in the goals of the researchers.

Research in these areas has focused on understanding how cognitive maps are formed, how they are used, the effects of the environment on their formation and use, the design of navigational aids, the design of geographic information systems, and the tracking of criminal behavior. While most studies focus on the accuracy of mental representations, the underlying focus has been on the contribution these representations make to the achievement of individual goals and objectives (Canter, 1991).

Literature Review

Structure of Cognitive Maps and Environmental Knowledge

The concept of a unitary knowledge structure, i.e., a cognitive map, is erroneous. Environmental knowledge probably resides in several locations and forms. When needed, it is brought together to support spatial behavior. The task and environment influence the form and content of the knowledge applied at any one time.

In many cases, people's environmental knowledge is incomplete and inaccurate. Inconsistencies and inaccuracy in spatial behavior reflect the incompleteness, distortion, and asymmetries in this knowledge (e.g., Anooshian, 1996; Lloyd & Cammack, 1996; Sadalla, Burroughs, & Staplin, 1980). For example, a common result of distance-estimation is asymmetrical estimates between two points. The estimated distance from A to B is consistently different than the estimated distance from B to A.

The inaccuracies in people's cognitive representation of the environment arise from an interaction between complex environments, existing environmental knowledge, and navigation goals. Even if an environment can be objectively defined, people encode the environment differently. People select the salient aspects of their environments based on past experience in their own navigation and the current navigational needs (Golledge, 1991c). As would be expected, given these interactions, the inconsistencies in knowledge are not common across individuals (Lloyd & Heivly, 1987).

Knowledge of the environment also contains non-spatial information. (McNamara, Halpin, & Hardy,1992; Hirtle & Jonides, 1985). Most navigation imbues environmental knowledge with meaning because the person's goals in navigating are personally-relevant. This is one of the difficulties in defining the term "landmark." Landmarks are meaningful to individuals with certain goals. Landmarks useful for one navigation task may be meaningless for another task.

Personal events and actions, i.e., episodic memory, also affect environmental knowledge. The acquisition of spatial knowledge is based, mostly, on direct experience, i.e., moving through the environment (Gale, Golledge, Pellegrino, & Doherty, 1990). During the early stages of learning a new environment, much of the environmental knowledge is stored as episodic memory. Since each individual selects and encodes personally-relevant cues while encoding environmental information, acquisition of environmental knowledge is highly individualized. Even in complex environments, many aspects of the environment can also be ignored without adverse effects on navigation (Gale, Golledge, Pellegrino, & Doherty, 1990).

Several researchers (Hirtle & Jonides, 1985; McNamara, 1986; Hirtle, 1995) propose that environmental knowledge is stored in a hierarchical or partially hierarchical form. In hierarchical models, higher levels of the hierarchy contain less detailed knowledge than lower levels. As one progresses farther down the hierarchy, each node represents a smaller and smaller part of the environment. Partially hierarchical models allow relationships between lower-level nodes to be encoded without passing through the connecting higher-level nodes. Hierarchical clusters are formed by semantic grouping of locations/objects/buildings and by environmental characteristics.

The level of detail in the hierarchy may be a function of environmental scale and the person’s purpose for being in the environment. One would expect, for example, that the cognitive map of a New York City taxi driver would differ in content and level of detail from that of a New York City subway operator. Both people live in the same environment and travel throughout the city. Yet their knowledge of the city layout may differ greatly.

Distance relationships between points, within or between hierarchical clusters, are determined by characteristics passed up or down within the cluster. At lower levels in the hierarchy, the relationships among nodes is topological. Between-cluster measurement is probably influenced by distance between dominant reference points (Golledge, 1991c). As mentioned earlier, the cartographic map metaphor does not accurately describe cognitive representation of the environment. A two-dimensional or three-dimensional structure, with metric, Euclidean relations, does not exist.

Although semantic grouping affects the storage and retrieval of spatial knowledge, it is not clear whether semantic knowledge and spatial knowledge are integrated into the same structure. Some researchers support the contention that one structure holds both types of information (e.g., Merrill & Baird, 1987). Others, (e.g., Clayton & Chattin, 1989) propose that spatial and semantic knowledge may be stored in different structures. Yet both sets of researchers agree that semantic information can assist the encoding of spatial information and can facilitate its retrieval. As shown by Golldege (1991c) and Hirtle and Mascolo (1986) the ease of encoding and retrieval alters memory for the environment.

Spatial Knowledge

This section describes empirical research on the content and structure of environmental knowledge of large-scale environments. In most instances, the environments are naturally-occurring environments which participants learned through direct navigation. These studies also employ several of the procedures and dependent measures used in this research.

Reference Points. Reference points are salient locations or objects possessing strong semantic relationships with several other locations. They define a region through perceptual or symbolic significance (Holding, 1992). Reference points and landmarks are not synonymous. A landmark is a physical feature of a route which signals a navigational decision, or a physical feature of a region permitting maintenance of geographical orientation.

Sadalla, Burroughs, & Staplin (1980) studied the function of spatial reference points as points around which environmental knowledge is arranged. They believed reference points define the location of a larger set of non-reference points. Each reference point is associated with a set of non-reference points. The distance between a non-reference point and its reference point may be defined in terms of proximity, i.e., the relationship is topological. The relationship between two non-reference points is found by establishing the relationship between two reference points and then between the reference points and the non-reference points. They studied memory for a college campus.

In the first experiment, participants indicated the distance between two points by showing their location on a grid. For each pair, the reference point was shown as an origin or destination. They found asymmetry in distance estimates when one of the points was a reference point and the other was not. When the origin was a reference point, the distance to the non-reference point was estimated to be shorter than when the origin was the non-reference point. When neither of the points was more salient than the other, there was no asymmetry in the estimated distances.

In a second experiment, 15 locations were selected to create two types of prime-target pairs. The primes were neutral locations, i.e., they were neither high nor low reference locations. The targets were either high reference or low reference locations. Triads were created in which a neutral location was equidistant from a high and a low reference point. When presented with the prime and target, participants responded if they thought the pair were farther or closer than 600 yards. They found the reaction time (RT) for neutral-low pairs was greater than the RT for neutral-high pairs. Participants responded faster to neutral-high pairs than to equidistant neutral-low pairs. Accuracy was high and equal for both types of pairs.

In a third experiment, they investigated the effect of reference points on direction judgments. As in the previous experiment, prime-target pairs of locations were created. The prime was either a high or low reference point. The target was a neutral location. Participants were shown a spatial relationship between the prime and the target. They had to verify the accuracy of the proposed direction between the prime and target. RT was faster when the high reference location was the prime compared to when the low reference location was the prime.

The results of these three experiments suggest that knowledge of large-scale environments contains reference points around which other, non-reference points, are organized. The cognitive distance between reference and non-reference points is asymmetrical. Orientation judgments are made faster when the origin is a reference point. This suggests that the cognitive location of many points is stored or retrieved in relation to a smaller set of reference points. If spatial knowledge is hierarchically structured, reference points would occur at a higher-level of the hierarchy than non-reference points. The asymmetry of the representation also suggests that the spatial location of non-reference points is stored as a topological relationship with respect to a reference point. It does not appear that there is a metric representation of the environment.

Spatial Hierarchies and Environmental Features. McNamara (1986) investigated how spatial relations among objects in an environment are encoded in memory. He arranged object names, on the floor, in a 20 x 24 ft. space divided into four regions of equal size, i.e. a 2 x 2 grid. The regions were separated by black lines on the floor. Two groups learned the locations of the objects through direct experience. One group could move in the space without regard to the black lines. The other group had to treat the lines as boundaries. To move from one region to another the participant had to walk around the line dividing the two regions. McNamara was interested in the effect of these spatial regions on distance estimates within and across the regional boundaries. He arranged the objects so that there were equidistant intra-region and inter-region object pairs. After participants memorized the location of the objects, McNamara tested their memory for the environment using object-name recognition, direction estimation, and Euclidean distance-estimation.

He used a priming task for object-name recognition. An object name was presented, as a prime, followed by a target name. The participant had to indicate whether the target was one of the objects whose locations they had memorized. Participants' reaction time (RT) to the target was faster when the target was primed by an object in the same region compared to priming by an object in a different region. Participants' RT was faster when the target was primed by a closer object compared to priming by a more distant object. The size of the distance effect was larger when the prime and target were in the same region than when they were in different regions.

Participants estimated the direction between inter-region object pairs. McNamara found that direction judgments were distorted to correspond with superordinate relations between the objects. In other words, for two objects in different regions, the regional alignment affected the direction estimation. If the two objects were in vertically-aligned regions, direction estimates were distorted so that the objects were more vertically aligned than they originally appeared. Similarly, if the two objects were in horizontally-aligned regions, direction estimates were distorted so that the objects were more horizontally aligned than they originally appeared. The size of the distortions depended on the distance between objects. As the distance between the objects increased, the distortion decreased.

Regional boundaries and object distance also influenced distance estimations. Participants underestimated distance between objects in the same regions and overestimated distances between objects in different regions. They overestimated distances between close objects and underestimated distances between far objects. The size of this effect was smaller for objects in the same region than for objects in different regions.

The results suggest that objects in the same physical region are closer, in memory, than objects in different regions - even if the Euclidean distance between intra-region and inter-region object pairs is equal. The distortion effects of the boundaries on distance and direction estimation also suggest that memory for inter-region relations is encoded less accurately than for intra-region relations.

As a result of this research McNamara proposed that spatial knowledge is stored in a partially hierarchical structure. In a hierarchical structure, the spatial knowledge is stored in a branching tree. Higher levels of the tree contain more general knowledge. Lower levels contain more detailed knowledge. In a partially hierarchical structure, spatial relations among lower-level nodes attached to different higher-level nodes, i.e., in different regions, can be directly encoded.

Subjective Influences on Spatial Hierarchies . McNamara showed that spatial proximity and environmental characteristics can affect the structure of spatial memory. Hirtle and Jonides (1985) showed that spatial memory is influenced by factors other than physical characteristics of the environment.

Hirtle and Jonides used recall order and distance-judgments to study the structure of memory for a college town and campus. They asked students at the University of Michigan to memorize and recall 32 landmarks in central Ann Arbor (the town in which the university is located). All of the students had attended the university and had lived in the town for at least 2.5 years. There were 14 recall trials. Four trials were uncued free recall. On ten trials, participants were cued with a location name.

For the distance-judgment tasks, the researchers created triplets of locations in which two anchors were assigned to one target. The distances from the anchors to the target were approximately equal and the anchors were in different directions from the target.

There were two distance-judgment tasks. In the first task, participants were shown the names of two locations, in sequence, and indicated whether the distance between the two locations was larger or smaller than a standard distance, i.e., a modulus. The second task was a magnitude-estimation task. Participants gave a distance estimate, from 1 to 100, for the distance between two locations.

Hirtle and Jonides used the ordered-tree algorithm to analyze the recall protocols. The analysis output is an ordered tree with unidirectional, bi-directional or non-directional clusters. The clusters indicate the order in which subsets of locations are recalled consistently across all cued recall trials. There was similarity in recall strings across participants which suggests there is similarity in memory representation of the campus and town. They assessed the validity of the trees by seeing if the trees helped predict performance in the distance-judgment tasks.

In the first distance-judgment task, the distance between locations was either shorter or longer than the standard. Some location pairs were intra-cluster pairs. Some were inter-cluster pairs. For short distances, participants tended to perceive incorrectly a distance between locations as longer than the standard when the locations were in different clusters. For longer distances, participants tended to perceive incorrectly a distance as shorter when the locations were within the same cluster.

In the magnitude-estimation task, participants' estimates were accurate for intra-cluster and inter-cluster distances. Inter-cluster distance estimates were greater than estimates for intra-cluster distances of equal length.

The results suggest that the subjective hierarchies found in the recall task can affect judgments about the spatial relationship between locations by (1) exaggerating inter-cluster distances, and (2) attenuating intra-cluster distances. The evidence suggests that spatial processing is a function of spatial and non-spatial components.

Hirtle and Jonides concluded that semantic (i.e., non-spatial) information affects both encoding and retrieval of spatial information. If the semantic information affects a person's ability to access spatial information, the semantic information will affect the person's cognitive map of the environment. For example, the ease of access to spatial information alters the perception of distance and direction.

Hirtle and Mascolo (1986) looked at the effect of semantic labels on the acquisition of spatial information from maps. Two maps of 10 points were constructed using the labels from two conceptually distinct sets of locations (derived experimentally). The layout of the points on the two maps was identical. The points on both maps formed eight critical triads. Each triad formed an isosceles triangle. The distance between the anchor and two targets was equal. One of the targets was within the same conceptual set, the other target was in the other conceptual set. The difference between the two maps was the position of the two labels. Hirtle and Mascolo expected that swapping the position of two labels would affect the clustering of points.

Participants learned the locations on one map through a series of study-reconstruction periods. They studied the map and then, when presented with two anchor locations, placed points in relation to the anchors. The purpose of this task was to focus learning on the relationships between points rather than on absolute locations.

After learning the map, participants performed a distance-estimation task and a comparative distance-judgment task. The distance-estimation task was a magnitude-estimation task. In the comparative-judgment task, participants indicated which of 2 points was closer to a referent.

The effect of clustering was found for both dependent measures. In the magnitude-estimation task, participants' estimates of intra-cluster distances were shorter than estimates of equal-length inter-cluster pairs. Similarly, in the comparative judgment task, participants judged intra-cluster pairs as closer than equidistant inter-cluster pairs.

In a second experiment, they tried to create semantic clusters by manipulating the presentation of locations during map learning. While learning the map, one location from each conceptual set was always presented with locations from the other conceptual set. They were trying to force the semantic clustering of locations. The dependent measures were the same as in the first experiment. The results were similar to those of the first experiment which suggests that the learning strategy had no effect on clustering of locations.

The authors concluded that semantic labeling of points can produce semantic clusters which alter memory for spatial locations. Clustering appears to be the result of the integrated storage of semantic and spatial information. The verbal labels of the points affect encoding and retrieval of the location of the points. Semantically-related labels and locations are encoded together. During retrieval, semantically-related labels and points are remembered as being closer in space than semantically-unrelated points.

Functional and Spatial Relationships. Merrill and Baird (1987) investigated the conditions under which priming occurs in a lexical decision task. In many cases, response time is significantly shorter when the target word is frequently associated with the prime. In the context of environmental knowledge, association can be defined semantically or spatially. The relationship between locations is influenced by the physical separation of the locations and the subjective distance between them.

In the first experiment, they measured perceived relatedness among buildings on a college campus and in the surrounding town. The intent was to determine which aspects of the buildings were most relevant to judgments of relatedness. Participants sorted index cards containing names of all campus buildings and some buildings in town. They sorted the piles according to "what seems to go together" and were told to use as few piles as possible. Inspection of the piles showed that some participants used functional groupings while others used spatial groupings. Functional sorting was more prevalent than spatial sorting.

In a second experiment, participants were presented with prime-target pairs of building names. Participants were asked to indicate if the two buildings were both local, i.e. they responded “Yes” or “No.” The prime-target pairs of local buildings were created so that there were three types of association between pairs: spatial and functional, functional-only, and no association. They found that RT for spatial and functional pairs were shorter than RT for functional-only and unrelated pairs. Reaction-time for functional-only pairs did not differ from RT for unrelated pairs.

In a third experiment, participants wrote down the first location name that came to mind after viewing another location name. Most responses were related to the stimulus words both functionally and spatially. If there was a functionally-related building nearby, it was most frequently cited. If there was no functionally-related building nearby, the most frequently named building was spatially-proximal but functionally-unrelated. In the cases where there were several equidistant buildings, the relative prominence of the buildings was influential.

The fourth, and final, experiment, employed the same task as in the second experiment. Three types of prime-target pairs were created: (1) prime-target pairs of spatially proximal but functionally unrelated buildings were formed from the primes and responses in the third experiment; (2) pairs of buildings that were spatially proximal but functionally unrelated and were rarely or never given as responses in the third experiment; (3) pairs of buildings that were neither spatially proximal nor functionally related and did not appear to be related based on the results of the third experiment. There was no priming effect when the prime was a spatially proximal but functionally unrelated building.

The authors concluded that spatial relationships are not the sole source of organization in spatial memory. Functional relationships also influence the storage and retrieval of spatial information. Additionally, priming effects can be found when the prime-target relationship is functional only but the effect is small in comparison to the effect of a spatial and functional relationship.

McNamara, Halpin, & Hardy (1992) wanted to know if the non-spatial facts would be integrated into the spatial knowledge. They had participants learn the spatial layout of a college campus and learn historical, functional, or architectural facts about the campus buildings. Knowledge integration was assessed by comparing performance between two conditions: (1) priming by a fact about a close building and (2) priming by a fact about a distant building.

In the first experiment, participants saw either a fact or a building name. They had to indicate on which campus the building or the building associated with the fact was located. There was a significant spatial priming effect. RT for a building or fact was faster when primed by a close building or fact for a close building in comparison to priming by a far building or fact for a far building.

In another experiment, participants were presented with prime-target pairs in one of three experimental conditions: (1) a fact about a building primed the name of the building, (2) a fact primed the name of a near building, (3) a fact primed the name of a far building. On each trial, the prime was displayed, followed by the target. Participants had to decide on which campus the building was located. RT was controlled because an accuracy-RT trade-off had been apparent in a previous experiment. In this study, error rate was used as the dependent measure. The error rate was greatest for pairs in the far condition and smallest for pairs in which a fact about the building primed the building name.

The results of these experiments suggest that spatial and non-spatial information can be integrated in the same memory representation. The authors compare these results to those of other experiments (e.g., McNamara, Altarriba et al., 1989) in which participants had to distinguish between real building names and fake names. No priming effect was found when the distance between primes and targets was manipulated.

The authors conclude that spatial memory contains at least two components: 1) a hierarchical nonmetric representation that encodes spatial relations such as relative location, and 2) a metric spatial representation that encodes distances between locations. Location judgments, like those in these experiments, rely on the metric representation. Recognition judgments, like those in McNamara, Altarriba et al. (1989) use the nonmetric representation. Spatial priming does not occur in recognition tasks because location is not stored in a categorical manner. Spatial priming occurs in location-judgment tasks because people have to access their spatial representation. (this does not mean that the metric representation is accurate. It means that some interpoint distances have been stored.)

In addition, the current results suggest that the facts about the campus buildings were stored with the metric information- otherwise the priming would not have occurred. Spatial knowledge and non-spatial knowledge are integrated into the same memory structure.

Summary. The results from the research reviewed in this section illustrate the ways in which the cognitive representation of the environment differs from the environment itself. McNamara (1986) found evidence for a partially hierarchical knowledge structure for spatial knowledge. Sadalla, Burroughs, & Staplin (1980) showed that spatial memory of large-scale environments is anchored around reference points. When spatial memory is represented as a hierarchy, these reference points are positioned at a higher level in the hierarchy than non-reference points. Decisions about distances and direction are made more quickly when using a reference point as the origin. Hirtle and Jonides (1985) and Merrill and Baird (1987) both demonstrated that spatial processing is a function of spatial and non-spatial components. McNamara, Halpin, & Hardy (1992) concluded that spatial relationships are not the sole source of organization in spatial memory. Functional relationships also influence the storage and retrieval of spatial information.

Environmental Characteristics

This section describes research on the influence of environmental characteristics on navigation and memory for the environment. The environment plays an important role in navigation and the development of cognitive maps. During navigation, a person's goals interact with knowledge of the environment. Knowledge of the environment affects the formation of plans based on the affective and (non)metric spatial knowledge available to apply to the task of planning and executing the route. Navigation, in turn, affects knowledge of the environment. As navigation succeeds or fails, the person's cognitive map is modified (Kitchin, 1994).

Errors in Navigation. Williamson and Barrow (1994) studied navigation errors in everyday behavior. They found that errors in navigation are most often due to environmental factors or inattention. They asked participants to record instances of problems they experienced while traveling. The authors classified the errors into nine categories. Four types of errors accounted for 72 percent of the errors. The four categories were:

- Turning in the wrong direction in places where the participant should have turned in the opposite direction or not turned. These errors occurred most frequently in familiar environments.
- Missing a turn by passing by the turn or not perceiving the turn. These errors occurred most frequently in familiar environments.
- Inability to plan or choose a correct route resulting in a navigation error. These errors occurred most frequently in unfamiliar environments.

- Misconception of location by realizing the current location was not the expected location or did not appear as expected. These errors occurred most frequently in familiar environments.

Participants, when recording the errors, were also asked to describe possible reasons for the errors. The reasons were classified into five categories. Three of the categories accounted for 90 percent of the errors. These were:

- Environmental causes such as (a) inadequate or misleading signs, (b) perceptual confusion arising from homogenous surroundings or unavailability of landmarks, (c) complexity of roadway or hallway layout, (d) changes in the environment since the last time the participant had visited.
- Inattention to current location or progress along a route.
- Inadequate knowledge of the location of the destination or appearance of the destination. This type of error was apparent when traveling new routes in a familiar environment. The participant may not recognize a familiar landmark from a novel location. It also occurred when planning routes to a new location. Planning and preparation were not sufficient.

The types of errors and their causes suggest that environmental factors can cause navigation errors. Three of the four most frequent errors can be attributed to environmental causes. Only the participant's inability to plan a route can be solely attributed to lack of knowledge or planning by the participant. Of the causes proposed by the participants, 43 percent of the errors are attributed to environmental causes.

Williamson and Barrow's (1994) participants recorded problems with navigation in an urban environment. Syrotuck (1979) reviewed the movement of people lost in the wilderness. His conclusions indicate that environmental characteristics affect these people’s navigational choices.

Natural routes exist which lead the lost person in a particular direction. These include game trails, false shoulders, angled ridge lines, old railroad beds, and connected clearings. In cases where people lose sight of their trail, they don’t realize that brush or trees may change their view of a readily accessible trail. This happens more frequently when people move downhill from the trail into a clearing. Similarity of terrain also leads people to think they are in one place instead of another.

Syrotuck also found that some people travel the path of least resistance- regardless of direction. Alternative paths were chosen based on "looks." Almost all people traveled downhill, even when it was not the way back to their destination.

As shown by the previous two studies, environmental characteristics can affect navigation. Garling, et. al. (1986) and Weisman (1981) list three classes of environmental characteristics that should be considered when studying navigation in a human-made environment: differentiation, visual access, and complexity of the layout.

- Differentiation refers to different sections of a building being distinguishable.
- Visual access pertains to whether different areas of the building can be seen from other areas.
- Complexity of layout, in a building, refers to the spatial layout of the hallways and rooms.

The research described in the following section addresses environmental complexity. These articles focus on the effects of route length, turns, and changes in elevation on route and survey knowledge.

Route Characteristics. Byrne (1979) examined the effect of route length, number of turns, and complexity of surroundings (i.e., rural or urban environments), on route length estimates. Participants estimated route lengths for routes in urban or rural settings, of 300m, 500m, or 750m, and were straight or had 2-4 turns. Distance was estimated using a magnitude-estimation procedure. Byrne found significant effects for all three independent variables. Rural routes were judged to be longer. Straight routes were judged to be shorter. Shorter routes were overestimated in comparison to longer routes.

In a second experiment, participants were asked to draw road junctions on a piece of paper. True junction angles varied from 60-70 degrees or 110-120 degrees. He found that most estimates, for both conditions, were closer to 90 degrees.

Byrne concluded that environmental information is stored heuristically. Instead of a metric representation containing veridical distance and direction, he proposed that the mental representation is a network map which preserves topological relations, i.e., order of locations and turns. Neither the distances between locations nor the precise angles at which roads meet are encoded.

Changes in Elevation. Garling, Book, Lindberg, and Arce (1990) looked at how knowledge of elevation is acquired. In the first experiment, participants were given a street map, without elevation information, and asked to compare two locations in their town. They had to choose the higher location and estimate the difference in elevation in meters. The true difference in elevation ranged from 5 to 48 meters. Participants were accurate (70% to 100% accuracy) in choosing which location was higher. Their analysis of the elevation difference estimations was not conclusive. However, the choice data suggest that location elevation is stored as part of spatial knowledge.

In a second experiment, participants performed a choice reaction time task. Garling et al. presented them with two location names in sequence. The first name appeared and then the participant pressed a key to make the second name appear. Participants had to indicate which location was either higher or lower. The task changed across trials. RT was measured. They found a significant difference in RT for pairs of locations. The difference did not seem to be related to the distance between the two locations. Correlations between distance and RT were small and negative. Instead, the difference appeared to be related to the difference in elevation. Participants took longer to choose between two locations when the difference in elevation was smaller. The absence of a distance effect and the presence of an elevation effect suggest that elevation and route distance can be retrieved separately. One possibility is the use of elevation reference points which are used to judge relative elevation. This could explain the lack of a distance effect.

Montello and Pick (1993) had participants learn two routes in and around several buildings. One route was below the other and below ground. Participants learned each route separately. Each route contained 15-20 turns, did not retrace or cross themselves, and ended where they began. Each route contained four landmarks that were vertically aligned between routes. The top route was 500 m. The bottom route was 530 m.

There were 3 phases: learning, integration, and testing. Each participant walked one of the routes. During this walk, the experimenter stopped the participant and named the landmarks. Participants walked the route again but provided landmark name and distance information before reaching the first landmark. After completing the second walk, the participants named the landmarks in the order they appeared on the route. They then went to the starting point of the second route via a route that took them away from the original route. It was not the shortest route between the two starting points. They learned the second route in the same manner as they learned the first route.

Integration occurred in one of three conditions. In the first condition, participants walked back to the start of the first route and received the integration instructions. In the second condition, participants received the instructions at the start of the second route. In the third condition, participants walked from the start of the second route to the start of the first, via a stairway leading directly between the two, and back again. They then received the integration instructions. In all conditions, the instructions told the participant that the two routes were vertically-aligned (i.e., one route was above the other route). Participants then walked the route at whose start point they received the integration instructions. At each landmark, they pointed toward the other landmarks. RT and azimuth were recorded.

Montello and Pick found that azimuth error was greater when pointing toward landmarks on the other route. However, the accuracy of pointing toward every landmark was less than chance which suggests the participants had developed survey knowledge of the two routes. The location at which participants received integration instructions or the means of traveling between the two routes did not affect pointing accuracy. RT was greater when pointing toward landmarks on the other route.

Floorplan Complexity. O'Neill (1991a) attempted to develop an objective measure of the physical environment and measure its influence on cognitive mapping and navigation. He proposes that floor plan layout greatly influences navigation and a person's ability to develop an understanding of a building's layout.

His measure of floor plan complexity was based on the topological connections between choice points. A choice point is a location where a person must choose between two or more directions of travel. O'Neill considered intersections of two or more hallways and turns, where there is no intersection, as choice points. He emphasized the importance of choice points in the development of cognitive maps because people make navigation decisions at choice points.

O'Neill proposed the InterConnection Density (ICD) as a measure of floor plan complexity. It represents the density of paths between locations. ICD is the average number of choice points directly connected to a choice point. This is calculated by summing, across all choice points, the number of choice points directly connected to each choice point and dividing by the number of choice points.

In this experiment, participants navigated through three environments with ICDs of 2.4, 2.45, and 2.54 respectively. Route distance was equal for the three routes. Participants learned the environment first by looking at a series of photographs depicting choice points. Then they were asked to travel the route. Navigation performance was measured by (a) time required to travel from start to finish, (b) the number of incidents of backtracking, and (c) the number of wrong turns.

There were significant differences, between the route with the highest ICD and the lowest ICD, for travel time, number of backtracking instances, and number of wrong turns. For each measure, the value was greater for the route with highest ICD.

In similar studies in different environments, O’Neill (1991b; 1992) found a similar relationship between ICD and navigation.

Summary. As shown in the preceding section, route length, the number of turns, and changes in elevation affect memory for distance and direction. Byrne (1979) asked people to estimate route distances for routes varying in setting (urban or rural), length, and number of turns. He found that urban routes were judged to be longer; straight routes were judged to be shorter; shorter routes were overestimated. Garling, Book, Lindberg, and Arce (1990) studied the ability of people to identify changes in elevation. The results suggest that lateral distance is not stored in the same manner as vertical distance. Montello and Pick (1993) assessed whether vertically-aligned (i.e., on different floors of the same building) routes could be integrated through direct experience. The results suggest that vertical integration of routes is more difficult than integration of routes on the same elevation. O’Neill (1991b, 1991c, 1992) has concentrated on the influence of floor plan complexity on navigation. His research (and Weisman’s) suggests that as ICD increases, navigation performance decreases.

Virtual and Simulated Environments

Virtual environments, as presented in this research, have only been possible for the past 15 years. However, simulated environments are not restricted to virtual environments. As shown by the research reviewed below, film, models, and video have been used to study cognitive maps developed during interaction with simulated environments.

The research suggests that the same physical characteristics of the real-world that are important in the development of cognitive maps are also important in the development of cognitive maps of virtual environments. Darken (1996) lists characteristics he considers the defining characteristics of virtual environments (extent, detail, density, scale, dimension, and restriction) which capture many of the same concepts used by Garling, et. al. (1986) and Weisman (1981).

This section, like the previous section on environmental characteristics, reviews research employing virtual environments to study environmental cognition.

Virtual Environments and Environmental Characteristics. Darken and Sibert (1996a) showed how the structure of a virtual environment affected navigation in the environment. The environment was a large open sea with islands separated by large distances. Participants had to search the space for ships. Their perspective on the environment was that of a pilot in an airplane. In the two conditions in which grid lines were superimposed on the environment, participants searched the space by following the grid lines. In those conditions in which grid lines were not provided, participants anchored their search to the islands or to the edges of the environment.

They found that movement in sparsely-populated space led to disorientation much of the time. Participants in the environments without the grid lines were less able to form an accurate representation of the environment. People need structured movement for effective navigation and spatial-knowledge acquisition.

Darken and Duckworth (1994) also showed that a relationship exists between the tools and cues in the virtual world and the behavior and strategies employed by people navigating in that world.

Using an environment similar to that used by Darken and Sibert (1996), participants explored the virtual space to see as much of it as possible. They then searched for a target. Upon finding the target, they were asked to return to the start position. Darken and Duckworth performed a GOMS analysis of navigational behavior. Their analysis reveals that the environment affected navigation through the use of landmarks and districting.

Successful exploration relied on maintaining sight of the landmarks. As shown in the three-step process below, participants used landmarks as an orienting feature while exploring the space.

Table 1 Procedure for Using Landmarks to Navigate in a VE

1. Acquire orientation and position information by getting directional and distance information from landmarks.
2. Learn space by moving through space while maintaining orientation and position with respect to landmarks.
3. If space is not partitioned perform an organized and exhaustive search. If space is partitioned, search partitioned areas systematically.

They also found evidence of "districting", which they define as the partitioning of the space into smaller units which are more easily searched. Districting occurs when some aspect of the environment allows the partitioning of the environment. When this is possible, participants followed these steps to search the space:

1. Acquire orientation and position within district.
2. Move along district borders and note relationship to immediate neighbors.
3. Learn space by moving within a district. Note relationship of objects within district.
4. Search space for target within district. Search new district if target is not found.
5. If orientation of district and district alignment is lost, move to neighboring districts until it becomes familiar. Restart search if district border connections are lost. Backtrack within district to reestablish district orientation.

<u>Virtual Environment (VE) as a Real-world Surrogate</u>. Arthur, Hancock, and Chrysler (1993) examined virtual reality as a means for studying tasks requiring spatial representation. Participants studied the arrangement of nine objects on the floor. They viewed the objects in either a virtual world, the real-world, or the real-world from a fixed viewpoint. After studying the objects, participants rank-ordered the distance between the three pairs.

The objects were arranged in a 16' x 18' blackened room. The VE consisted of the same nine objects shown at the same angle as the real room and in the same arrangement. In the real-world and VE conditions, participants could move about the room to view the objects from different angles. In the real-world, fixed viewpoint, participants had to view the room from one location and with one eye.

They found no difference between groups in estimating the distances between objects. These results suggest that VE can simulate spatial relations.

Bailey and Witmer (1994) trained people to navigate in a building or in a virtual environment of the same building. All participants studied route directions and photographs of landmarks for a complex route and then were assigned to one of three rehearsal groups: (1) VE rehearsal in VE building, (2) building rehearsal in the actual building, and (3) rehearsal through verbal rehearsal of route directions while referencing photographs. After rehearsal, all participants were tested for navigation performance in the actual building.

Route performance was measured by the number of wrong turns and travel time. Participants trained in the building made fewer wrong turns than those trained in the VE. Participants trained in the VE made fewer wrong turns than those trained verbally. There was no difference in travel time between the real-world and VE groups. Participants in both groups completed the route more quickly than participants in the verbal-rehearsal group.

Navigation Simulation. Gale, Golledge, Pellegrino, and Doherty (1990) compared navigation training in the real world and while watching a video tape of the same environment. Participants in the video training condition navigated poorly in comparison to those trained in the real-world. However, memory for scenes was equivalent between the two groups.

They had children (aged 9-12 years) learn two routes through an unfamiliar suburban neighborhood. Both routes had seven turns. Participants learned one route by traveling the route. They learned the other route by viewing a video tape five consecutive times. In the neighborhood condition, the experimenter led the participant on the first trial, when learning the route through direct experience. On the remaining four trials, the experimenter gave the participant little help. In both conditions, after the 1st, 3rd, and 5th trials on each route participants completed scene recognition tests. For routes learned via videotape, a final navigation test in the neighborhood occurred after the 5th learning trial.

For participants learning the route through direct experience, the time required to travel the route dropped from the 1st to the 4th trial. By the 3rd trial, the mean number of mistakes was effectively zero. The difference in errors across trials was significant as was the difference in travel time.

Navigation performance in the neighborhood following the 5th video trial was similar to performance during the first 3 trials in the direct experience conditions. Seeing the route five times on video was roughly equivalent to one traversal of the route in the field.

There was no difference in scene recognition between participants in the direct experience and video learning conditions. In both conditions, participants recognized views of choice points better than they recognized views of houses along the route. This suggests that choice points are learned first and better than non-choice points.

Goldin and Thorndyke (1982) compared the spatial knowledge acquired via direct navigation or simulated navigation through an environment.

Participants toured an unfamiliar area of Los Angeles, by bus or by viewing a film taken from a car on the same route. The tour lasted 24 minutes and contained eight buildings the experimenters designated as landmarks. The bus and film stopped briefly at each landmark before continuing the tour. Participants received one of the following types of supplementary information: (a) a concurrent description of the route which provided distances, directions, and street names, (b) a map prior to taking the tour or seeing the film, (c) or no supplementary information.

The participants were then given a landmark-recognition test, location-sequencing test, route distance-estimation test, orientation test, and Euclidean distance-estimation test. Goldin and Thorndyke proposed that the first test assessed landmark knowledge; the 2nd, 3rd, and 4th tests assessed route knowledge; the 5th test assessed survey knowledge.

They found that participants who saw the film recognized landmarks better than participants who took the bus tour and recognized non-choice points better than choice points. Tour participants recognized choice points better than non-choice points. Film participants who did not receive the concurrent description performed better than film participants receiving the concurrent description. There was no effect for supplementary information for the tour group.

Neither group performed well on the location sequencing test. Yet the difference between the two was significant. The film group performed better than the tour group. The type of supplementary information also affected accuracy. The concurrent description group performed worse than the other two groups.

There was no difference between groups in route distance-estimation. Goldin and Thorndyke attribute this to the use of travel time as the means of estimating route distance. Since this was the same for both groups, their performance should be the same. The type of supplementary information did not affect accuracy on this task.

Although both groups' accuracy was poor, tour participants were more accurate in orientation estimates than film participants. Participants provided with maps prior to the tour or film were less accurate than the control or concurrent description groups.

When estimating Euclidean distance between landmarks, there was no difference between the film and tour groups. Participants who received the map prior to viewing the film gave more accurate estimates than the other participants in the film group. All participants' estimates were less accurate than their route distance estimates.

The minimal differences between the tour and film groups suggest that exposure to a simulated environment can provide information similar to that of direct experience.

Hunt (1984) studied how people learn new buildings by simulating navigation through a building prior to arriving at the building. In this experiment, the simulation consisted of a small-scale three-dimensional model of the building and a series of slides following a path through the building. Participants were assigned to one of three conditions. In the simulation condition, participants viewed the slides and the model simultaneously before seeing the real building. In the building condition, participants traveled the simulated route in the real building. Participants in the control condition did not see the building or the simulation prior to testing.

There were two measures of environmental knowledge: "mental image" of the building, and navigation ability in the building. There were three tests to assess the participant's mental image.

- Participants matched photographs to the names of locations in the building.
- They arranged photographs in the order shown in the simulated or real route.

- They identified the shape of the building by picking from 1 of 4 shapes.
- They identified the floor on which a series of 9 rooms was located.
- They marked the location of 9 rooms on a plan of the building.

To test navigation ability, participants performed nine navigation tasks in which they traveled from one location to another in the building. The control group only participated in the navigation test.

Some of the tests required knowledge not shown explicitly in the simulation or on the tour of the building. Other tests were taken directly from the simulation or tour. The simulation group performed better than the tour group on those tasks that were not directly related to the simulation or tour. The simulation group also performed better than the control group in all but one of the tasks. In contrast, the tour group performed well only when the test assessed knowledge presented during the tour and in the same order as in the tour. The tour group performed better than the control on only five of the tasks.

The results suggest that identification of sites and sequential ordering are important but not sufficient for effective navigation. They also show that simulation can lead to an understanding of spatial arrangement of the environment.

Orzech (1986) evaluated the use of a simulated environment setting to enhance people's abilities to navigate in a building. She compared two simulation groups and a control group on their ability to navigate in a maze-like environment. Participants in the same-maze group interacted with a simulation of the same environment used for the navigation test. The simulation contained the same number of choice points and topological correspondence.

The different-maze group used a computer simulation that did not correspond to the real-world space. In both simulation groups, some participants received a map of the maze prior to their using the simulation.

Travel time in the simulation and real-world was one to two minutes. The maze was contained in a 34’ x 45’ area. After completing three simulation trials, participants were told to navigate through the real-world maze. They then returned to the start point.

Orzech found that only the presence of a map improved the same-maze simulation group above the other groups. Within the map condition, exposure to the same maze during simulation, resulted in fewer errors, faster times, and less distance traveled.

During the reversal task (walking back through the path from the target to the start), there was no effect of simulation. All groups improved, i.e., there were fewer errors, less travel time and shorter distance traveled, thereby indicating a rapid learning of the path.

She concluded that simulation is only effective if explicitly associated with the space being simulated. People need to understand the link between the simulation and the real-world. It may be necessary to link orientation, location, distance and direction between the simulation and world.

The improvement and lack of difference in the reversal task may be due to rapid learning of the environment or the inability of participants in the same-maze condition to rotate the simulated environment.

<u>Cognitive Representations of Virtual Environments</u>. Ruddle, Payne, and Jones (1997) performed three experiments to understand the accuracy of the participants’ knowledge as

they learned the layout of a large-scale VE. In experiment 1, participants navigated through a virtual building. Their navigation ability was measured longitudinally during 10 different journeys. One group learned the floor plan from a map, the other from controlled exposure to the VE. The VE had 135 rooms, of which 9 contained furniture. There were no landmarks or windows in the VE.

In the simulation condition, participants learned the navigational layout in nine sessions over nine days. In each session, participants visited each of the nine locations in a different order. In the first two sessions, they traveled to each location by following a verbal description of the shortest route. In the remaining sessions, they navigated without help but were subject to help if they did not find the location within 5 minutes. Map participants learned the floor plan by studying the map and then performed the same test as the simulation participants.

To measure knowledge of the building layout, participants in both conditions moved from one location to another. After arriving at a location, they pointed toward each of the other locations, indicated the straight-line distance to the other locations, and the route distance in feet or meters.

After extended practice, participants had near perfect navigation and route distance estimate ability within the VE. Their orientation was similar to people who had worked in the real building for 1-2 months.

Map participants were more accurate than VE participants in route distance and Euclidean distance-estimation. Simulation participants were more accurate in route distance-estimation than in Euclidean distance-estimation. There was no consistent tendency to overestimate or underestimate the Euclidean or route distances. There was no difference, between groups, in the accuracy of direction estimates.

In experiment 2, the authors investigated the effects of local landmarks and the development of survey knowledge through navigation. The VE contained ten named rooms. Each was filled with three-dimensional models of furniture. The remainder of the building was filled with 141 empty rooms. Landmarks appeared at hallway intersections in part of the VE. The landmarks were cubes covered with abstract paintings. They were symmetrical so they did not provide orientation information.

Participants learned the VE in nine sessions over one week. In each session, participants visited the ten named rooms. In the first session, they were guided by verbal instructions of the shortest route. In the second session, they were told to take the shortest route to the named rooms. In the remaining sessions, they navigated without any instructions. At the end of sessions 3, 5, 7, and 9, participants provided direction and Euclidean distance-estimations from each room to the other rooms.

Navigation improved in the part of the VE with landmarks and without landmarks. However, even after 9 sessions, the average distance traveled between rooms was twice the distance of the shortest route between the rooms. All participants noticed the landmarks and used them for navigation. They also indicated that characteristics of the hallway layout were also useful as landmarks. However, landmarks made no difference in navigation ability. There was no effect of landmarks on distance estimate accuracy. Direction estimates improved across trials but there was no effect of landmarks on direction accuracy.

The third experiment was identical to the second experiment except for the landmarks. The landmarks were changed from abstract paintings to three-dimensional models of everyday objects.

The only difference in the pattern of the results was found in the distance traveled between rooms. Participants traveled shorter distances in the section of the VE containing landmarks in comparison to the section without landmarks. There was no effect of landmarks on distance estimate accuracy or direction estimate accuracy.

Satalich (1995) showed that orientation performance increases when people training in a virtual environment are allowed to move freely through the environment. In this experiment, the VE was a U-shaped building measuring 100 feet by 100 feet and containing 39 rooms. The rooms and hallways contained objects and paintings. Participants viewed the world through a helmet-mounted display and controlled movement with a joystick. To learn the environment, they either explored the VE freely, followed a predetermined path, or were guided along the same path. In all three conditions, participants explored or toured the VE for 30 minutes.

After exposure to the VE, participants were given several tests of environmental knowledge. Direction estimates were measured by having the participants look in the direction of objects located out of the field of view. Then they estimated route distance and Euclidean distance between themselves and objects and between pairs of locations.

After completing the other tasks, they performed two navigation tasks. In both tasks, they were told to find the shortest route between two locations. One route required the inference of hallways not seen on the tour.

The passively guided and self-exploration groups both performed better than the actively guided group on the pointing task, route distance-estimation between the participant and an object, and Euclidean distance-estimation between two locations. For route distance-estimation between two locations, the self-exploration group was less accurate than either of the other two groups. For Euclidean-distance-estimation between the participant and an object, the self-exploration groups was more accurate than the other two groups.

In the first navigation task, the self-exploration group performed better than the other two groups. In the navigation task requiring survey knowledge, participants in the passive-guided condition performed better than participants in the self-exploration condition who performed better than those in the active-guided condition.

Williams, Wickens, and Hutchinson (1994) compared the effect of different levels of training fidelity on route and survey knowledge. In the first experiment, one group trained by studying a contour map showing the route the participants would fly in the second phase of the experiment. They rehearsed the route for 30 minutes. A second group flew for 30 minutes in a simulated three-dimensional environment. Half of these participants used a low-fidelity representation. The other half used a high-fidelity representation. For each participant in these conditions, their flight path was recorded. A third group viewed the flight path of a matched participant in the second condition.

Following training, all participants flew the route in a flight simulator using a map for reference. During the flight they were asked to indicate their position on the map. At the end of the route they were asked to fly a straight line back to the starting point without using the map.

The participants who flew the route during training flew the most accurate routes of all the groups. There were no differences between high and low fidelity simulation. The group that studied the map was the second most accurate. The group that viewed the simulation was the least accurate. There was no difference in performance on the return flight to the starting point. In flying directly back to the starting point, there was no difference in performance between groups.

The conditions were the same in the second experiment except that a map was not provided during the test flight. In this study, the participants that flew the simulator during training performed worse than the other two groups during the flight test. There was no difference in performance on the return flight.

There was no support for an advantage of higher fidelity rendering of scene detail. However, it is possible that the addition of more detail was in areas less important to navigation. Greater resolution may show an effect if added to other aspects of the environment. Secondly, the results are equivocal regarding the utility of passive video training.

<u>Summary</u>. The research reviewed in the preceding sections suggests that virtual and simulated environments can be used to study spatial cognition. Arthur, Hancock, and Chrysler (1993) showed that a virtual environment can be used to communicate spatial relationships among objects as well as a real-world environment. Bailey and Witmer (1994) trained people to navigate in a building by first navigating in a virtual representation of the building. Hunt (1984) showed similar learning through exposure to films and a model of a

building. Goldin and Thorndyke (1982) compared spatial knowledge acquired via direct navigation or simulated navigation (a film) through an environment. Participants in the film group performed better on tests of landmark knowledge and sequencing of pictures from the route. They performed worse in distance and orientation estimation. Neither group exhibited development of survey knowledge. Orzech (1986) compared navigation in a simulated environment and navigation in an equivalent real-world environment. Only when the simulation was explicitly connected with the real-world did it aid in navigation. Ruddle, Payne, and Jones (1997) showed that extended experience in a virtual environment can lead to navigation and spatial knowledge equivalent to that of people who have worked in the real-world environment. Satalich (1995) showed that orientation performance increases when people training in a virtual environment are allowed to move freely through the environment. Williams, Wickens, and Hutchinson (1994) found similar results in a flight simulator.

Summary

The research reviewed in this section investigated the influence of objective, physical characteristics of the environment and subjective interpretation of the environment and their effects on people’s cognitive maps.

Hirtle and Jonides (1985) and Hirtle and Mascolo (1986) showed that people store environmental knowledge based on subjective, non-spatial aspects of the environment- even when there is nothing, physically, to support the distortion of the layout during encoding or retrieval. Merrill and Baird (1987) found both functional and spatial relationships affect recall and RT on priming tasks. The integration of non-spatial knowledge into cognitive maps has been supported, (e.g., McNamara, Halpin, & Hardy, 1992) with similar studies.

One shortcoming of these studies is the lack of control over exposure to the environment. Most of these experiments used college students' knowledge of their college campus. As in most research in existing environments, there is no easy way to measure participant's experience in the environment prior to measuring their knowledge of the environment. In the one study that controlled exposure to the environment (Hirtle & Mascolo, 1986), the environment was presented in a top-down view and was composed of dots for locations, and location names. None of the research examining the effect of non-spatial knowledge on cognitive maps has required participants to learn the environment through navigation. Nor has the previous research controlled both the type of non-spatial knowledge and exposure to the environment. By controlling both factors and requiring navigation through the environment, it may be possible to understand better how non-spatial and spatial knowledge interact as both are acquired most often in the real-world, i.e., through direct navigation.

The research also suggests that environmental knowledge is stored in a partially hierarchical structure (McNamara, 1986). In hierarchical models, higher levels of the hierarchy contain less detailed knowledge than lower levels. As one progresses farther down the hierarchy, each node represents a smaller and smaller part of the environment. Relationships between lower-level nodes can be encoded without passing through the connecting higher-level nodes. While many of the studies, whose results support the concept of a hierarchical structure, evaluated knowledge of three-dimensional environments, the researchers treated the environments as if they were two-dimensional. When asking participants to provide direction and distance estimates, they did not measure or control changes in elevation. It is not clear how changes in elevation affect the hierarchical structure of environmental knowledge.

One limitation of using campus buildings as target locations is that straight-line distance and route distance are highly and positively correlated. That is, if two buildings are close together, the route between the two is probably shorter than the route between two buildings that are farther apart. Another problem with these environments is that the change in elevation across campus is minimal in comparison to the size of the campus. Although none of these studies addressed or controlled changes in elevation (with the exception of Garling et al., 1990; Montello & Pick, 1993 which I will discuss in the next paragraph), the correlation between elevation change, route distance, and straight-line distance is probably high and positive. As a result, it is difficult to know if environmental knowledge is encoded based on route distance, physical distance, elevation, or some combination of the three.

The results of Garling et al. (1990) suggest that elevation is stored independently of route distance. However, the level of exposure to the environment was not controlled. They were not sure that all of their participants had traveled between the landmarks used in their study. In other words, without knowing if the participants had route knowledge for routes between the landmarks, the relationship between elevation and route knowledge is difficult to ascertain. Montello and Pick (1993) had participants learn two vertically-aligned routes. They found that pointing toward landmarks on routes at different elevations required more time and was less accurate than pointing toward landmarks at the same elevation as the participant. The effect of participant location suggests that the difference in elevation created two separate hierarchical clusters for the routes, i.e., the locations at one elevation were encoded as one cluster and the locations at the other elevation were encoded as another cluster. It is not clear, though, whether the lack of integration between the routes reinforced the formation of separate clusters. If the routes had common locations so that the difference in elevation was not confounded with the difference in route, the hierarchical structure may have been different.

As shown above, there is a need to address the effect of elevation on cognitive maps. Indoor environments do not possess the limitations of the environments in the previous research. In indoor environments there are many instances in which route distance and straight line distance between points are not highly positively correlated. When two rooms are vertically aligned, on different floors, the straight line distance is usually much shorter than the route distance (unless you are in a firehouse or the Bat Cave and there is a firefighter's pole leading between the two rooms). By controlling the environment, the effect of elevation can be more easily assessed.

Two other physical characteristics shown to affect cognitive maps and navigation are route distance and the number of turns on a route (Byrne, 1979; O'Neill, 1991b, 1991c, 1992). Longer and more complex routes are more difficult to navigate. Memory for these routes is also less accurate than memory for shorter, simpler routes. Since most environmental knowledge is gained through direct navigation, the study of the development of cognitive maps should include a range of distances and turns to understand the effect of route complexity.

The research on virtual and simulated environments indicates that these environments can be used to create spatial knowledge. An advantage of virtual environments is the ability to control pre-experimental exposure to the environment. Unlike research in real-world environments in which participant exposure is difficult to control prior to the experiment, the researcher can be assured that the environment is new and all knowledge of the environment is acquired during the experiment.

Research Variables and Hypotheses

This research was done to answer the questions below. Each set of questions addresses the effects of one of the main areas discussed in the literature review: (a) non-spatial knowledge and its influence on memory for the environment, and (b) physical characteristics of the environment such as elevation, route distance, and route complexity. This section briefly discusses the prior research and then lists the research questions and hypotheses associated with each question.

Non-spatial Knowledge

Several researchers found that non-spatial information affects memory for spatial characteristics of the environment. Hirtle and Jonides (1985) found that distance estimates for distances between locations in different subjective (non-spatial) groups, were greater than estimates for equal-length distances between locations in the same subjective group. Hirtle and Mascolo (1986) showed that manipulation of non-spatial information influences memory for distances between locations. Merrill and Baird (1987) studied the integration of non-spatial and spatial information. They concluded that non-spatial information will not affect performance on a spatial task if the non-spatial information is the only source of association between locations. Together, these results suggest that the subjective groups formed by participants affect judgments about the spatial relationship between locations by (1) exaggerating inter-group distances, and (2) attenuating intra-group distances. Their results suggest that spatial processing is a function of spatial and non-spatial components.

Each of the hypotheses associated with non-spatial information is based on the following assumptions: (a) participants will form subjective groups of locations, (b) the basis for the groups will be non-spatial information in the environment, (c) these subjective groups will distort memory for locations in the environment, and (d) these distortions will be evident when participants are asked to provide estimates of distance and room location. It is not expected that the subjective groups will affect navigation or direction estimates. Navigation probably depends on environmental cues that are not available while estimating distance or room location. The environmental cues should be stronger than the subjective groups thereby reducing or eliminating the distortions caused by the groups.

1. Does non-spatial knowledge of the environment affect the accuracy of spatial knowledge of the environment?

H1: Route distance estimates will be larger when the origin and target are in different semantic groups than when the origin and target are in the same semantic group.

H2: Direction estimates for origin-target pairs from different semantic groups will be of equal accuracy, in elevation and azimuth, as estimates for origin-target pairs from the same semantic group.

2. Does non-spatial knowledge of the environment affect the speed with which decisions are made about spatial characteristics of the environment?

H3: When making a decision about a room location, the participant's RT will be smaller when the prime and the target are in the same semantic group than when they are in different semantic groups.

3. Does non-spatial knowledge affect navigation performance?

H4: Navigation on routes whose origin and target are in the same semantic group will take the same amount of time as navigation on routes whose origin and target are in different semantic groups.

H5: The number of elevation navigation errors on routes whose origin and target are in the same semantic group will be the same as the number of elevation navigation errors on routes whose origin and target are in different semantic groups.

Changes in Elevation

As shown by McNamara (1986), and Sadalla, Burroughs, and Staplin (1980), physical boundaries create subjective groupings of locations. In a multi-floor environment, participants might subjectively group the rooms on each floor. In other words, rooms on the same floor will be more closely associated in memory than rooms on the other floor. Subjective grouping of rooms should affect memory for room location. Although neither McNamara nor Sadalla, Burroughs, and Staplin used elevation as a means of physically separating locations, the effect should be the same. The separation of rooms across floors will distort the true distance and direction between rooms. Rooms on the same floor will be more closely associated in memory, because of the subjective grouping, which will make decisions about room locations faster.

4. Do changes in elevation affect the accuracy of memory for room location?

H6: Route distance estimates for origin-target pairs that are on different floors will be less accurate than for origin-target pairs that are on the same floor.

H7: Azimuth estimates for origin-target pairs that are on different floors will be less accurate than for origin-target pairs that are on the same floor.

H8: Elevation estimates for origin-target pairs that are on different floors will be less accurate than for origin-target pairs that are on the same floor.

5. Do changes in elevation affect the speed at which decisions are made about spatial characteristics of the environment?

H9: When making a decision about a room location, the participant’s RT will be shorter when the prime and the target are on the same floor than when they are on different floors.

6. Do changes in elevation affect navigation performance?

H10: Navigation on routes whose origin and target are on the same floor will take less time than navigation on routes whose origin and target are on different floors.

H11: The number of elevation navigation errors on routes whose origin and target are on the same floor will be less than the number of elevation navigation errors on routes whose origin and target are on different floors.

Distance between Rooms

Given the lack of consensus of the effect of distance between locations on distance estimates (Byrne, 1979; Ruddle, Payne, & Jones, 1997; Lloyd & Heivly, 1987), the hypotheses associated with distance are derived from the previous research, the characteristics of the VE used in this experiment, and this experiment's methodology. The results of Ruddle, Payne, and Jones suggest that navigation through a VE does not lead to consistent distortions of distance estimates. In their VE, the locations participants had to learn were spread uniformly throughout the VE. While learning the layout of the VE, through navigation, participants routes did not expose them to some locations more than others. In this experiments VE, while participants learn the environment, they will see the rooms at the shorter distances more often than they see the rooms at the longer distances. This increased exposure to the rooms at the shorter distance may provide a greater opportunity for developing metric knowledge of that part of the VE thereby making the distance estimates more accurate than estimates for rooms in the parts of the VE where metric knowledge does not exist. For the same reason, direction estimates should be less accurate for locations farther apart. Since direction estimates depend on distance estimates, the metric knowledge which may exist for the rooms at the shorter distances should lead to more accurate direction estimates. Finally, rooms that are located proximally should be more closely associated in memory (McNamara, 1986). The difference in the strength of association should be apparent in the difference in RT when making room location decisions.

7. Does route distance affect the accuracy of memory for room location?

H12: Route distance estimates for origin-target pairs that are farther apart will be less accurate than for origin-target pairs that are closer together.

H13: Azimuth estimates for origin-target pairs that are farther apart will be less accurate than for origin-target pairs that are closer together.

H14: Elevation estimates for origin-target pairs that are farther apart will be less accurate than for origin-target pairs that are closer together.

8. Does route distance affect the speed at which decisions are made about spatial characteristics of the environment?

H15: When making a decision about a room location, the participant's RT will be shorter when the prime and the target are closer together than when they are farther apart.

9. Does route distance affect navigation performance?

H16: Navigation on routes whose origin and target are farther apart will take more time than navigation on routes whose origin and target are closer together.

H17: The number of elevation navigation errors on routes whose origin and target are farther apart will be greater than the number of elevation navigation errors on routes whose origin and target are closer together.

Route Complexity

The hypotheses associated with route complexity rely on the algorithm proposed by Thorndyke and Hayes-Roth (1982). They proposed that participants estimate route distances by adding the estimated distances of each leg in a route. Participants estimate direction by estimating the angle at which the legs of a route intersect. As the complexity of a route increases (i.e., the number of turns increases), the participant must estimate a greater number of distances and angles of intersection. Each estimate presents an opportunity for error which suggests that more complex routes are more likely to lead to less accurate distance and direction estimates than less complex routes. The complexity of a route between locations may also influence the memory for room location. Rooms separated by routes with more turns will be perceived to be farther apart than rooms separated by routes with fewer turns. The difference in perceived distance may lead to subjective groupings of rooms which means that some rooms should be more closely associated in memory (McNamara, 1986) when they are perceived to be physically proximal. The difference in the strength of association should be apparent in the difference in RT when making room location decisions.

10. Does route complexity affect the accuracy of memory for room location?

H18: Route distance estimates for origin-target pairs that are separated by routes with turns will be less accurate than for origin-target pairs separated by routes without turns.

H19: Azimuth estimates for origin-target pairs that are separated by routes with turns will be less accurate than for origin-target pairs separated by routes without turns.

H20: Elevation estimates for origin-target pairs that are separated by routes with turns will be less accurate than for origin-target pairs separated by routes without turns.

11. Does route complexity affect the speed at which decisions are made about spatial characteristics of the environment?

H21: When making a decision about a room location, the participant's RT will be shorter when the prime and the target are separated by routes with no turns than when they are separated by routes with turns.

12. Does route complexity affect navigation performance?

H22: Navigation on routes with turns will take longer than navigation on routes without turns.

H23: There will be more errors during navigation on routes with turns than on routes without turns.

Summary

This research investigates the influence of environmental characteristics and semantic groupings on the development of route and survey knowledge acquired through direct navigation. As described in the previous section, there are limitations of the existing research on changes in elevation and the integration of non-spatial and spatial knowledge. In the research described here, participants learned a virtual environment and were tested for their knowledge of the environment.

Method

Overview of Procedure

In this experiment, the participants learned the locations of rooms in a virtual representation of a two-story building. The virtual environment was presented on a television screen and the participant controlled movement in the environment via a joystick. On each trial, the experimenter collected navigation performance data. Each participant completed the same number of learning trials.

After completing the learning trials, the experimenter administered several tests designed to measure route and survey knowledge of the environment. The tests were: route distance-estimation, target direction estimation, room location decision, and navigation performance.

Experimental Design

The experimental design differs for the learning trials and post-learning trial measures. For the learning trials and measures of route knowledge, the experimental design was a 3 (route distance) x 2 (route turns) x 2 (floor) within-participants design. The experimental design for the post-learning measures of environmental knowledge was a 2 (route distance) x 2 (route turns) x 2 (floor) x 2 (group) within-participants design. The tables below show the experimental design for the learning trials and the post-learning assessment of environmental knowledge.

Table 2 Experimental Design - Learning Trials

Floor					
First			Second		
	Turns			Turns	
Distance	0	2	Distance	0	2
1			1		
3			3		
5			5		

Table 3 Experimental Design - Post-learning Assessment - Known Routes

Floor					
First			Second		
	Turns			Turns	
Distance	0	2	Distance	0	2
1			1		
3			3		
5			5		

Table 4 Experimental Design - Post-learning Assessment - Novel Routes

Group	Elevation					
Same	Same			Different		
		Turns			Turns	
	Distance	0	2	Distance	0	2
	2			2		
	4			4		
Other	Same			Different		
		Turns			Turns	
	Distance	0	2	Distance	0	2
	2			2		
	4			4		

Independent Variables

There are four independent variables representing spatial and non-spatial environmental characteristics: Semantic Group, Floor/Elevation, Route Distance, Route Turns.

Semantic grouping was accomplished by naming locations in the environment. The location names were drawn from two groups of names. When navigating in the environment, participants traveled between rooms from the same group and rooms from different groups.

Elevation differences are achieved through the structure of the environment. The environment was the interior of a two-story building. Participants traveled routes on one floor or routes leading between the two floors. In the learning trials, this independent variable is referred to as Floor because the target room on each trip is on the first or second floor. In the post-learning assessment, the independent variable is referred to as elevation because the target room in on the same or different floor as the origin.

During the learning trials, there were three route distances and routes with zero or two turns. For the post-learning measurements, there were two route distances and routes with zero or two turns.

During the analysis of the learning trial data, trial number was treated as an independent variable. Trial number was entered into the analysis to reveal the effects of practice on the acquisition of route knowledge of the environment.

Dependent Variables

The dependent measures collected during the learning trials differ from those collected after completion of the learning trials.

Learning Trials

The learning trials are intended to assess the effects of route distance, route turns, and elevation on learning the location of rooms in the environment. The dependent variables, described below, capture navigation performance during and across the learning trials.

Time To Complete Each Route. Timing began when the participant moved from the start of the route and ended when the participant arrived at the destination and indicated that they had arrived at the destination. The participant indicated they had arrived by pressing a button on the joystick. Even if the participant traveled a route without errors or hesitation, the time required to navigate a longer route was always greater than the time required to navigate a shorter route. As a result, the raw time data are not an optimal measurement of navigation performance. Prior to analysis, the raw time data were transformed to a percentage of optimal time (POT) using the following formula: POT = (time on route - optimal time)/optimal time X 100.

Number Of Errors While Completing Each Route. An error was defined as: (a) missing a turn that takes the participant on the shortest route to the target from their current location, or (b) turning away from the shortest route. Turns were defined as any 90 degree (left or right) or 180 degree change in direction. As will be shown later, during the discussion of the floorplan, longer routes included more decision points than shorter routes. In other words, there were more opportunities to make errors on longer routes than on shorter routes. To account for the differences in the number of opportunities for errors, the raw error score was transformed to a percentage of possible errors (PPE) using the following formula: PPE =

((number of errors - number of decision points on the shortest route)/number of decision points on the shortest route) X 100.

Distance Traveled During Navigation. The distance traveled between the start and destination was measured by tracing the participant's route on a map of the virtual environment. Even if the participant traveled a route without errors or hesitation, the distance traveled on a longer route was always greater than the distance traveled on a shorter route. As a result, the raw distance scores are not an optimal measurement of navigation performance. Prior to analysis, the raw distance data were transformed to a percentage of optimal distance (POD) using the following formula: POD = ((distance traveled - optimal distance)/optimal distance)) X 100.

Distance Traveled On the Wrong Floor During Navigation. The distance traveled on the wrong floor was measured by tracing the participant's route on a map of the virtual environment. It is not clear how elevation knowledge is acquired while learning a large-scale environment. To account for the possibility that floor location is learned separately from distance location, the distance traveled on the wrong floor (a.k.a. elevation error distance (EED)) was measured as a percentage of total distance traveled using the following formula: (distance traveled - distance traveled on wrong floor)/(distance traveled) X 100.

Post-Learning Assessment of Environmental Knowledge

After the participants completed the learning trials, they provided route distance estimates, direction estimates, judged the location of rooms in the environment, and navigated novel routes. These dependent measures were used to assess the effect of route distance, route turns, elevation and semantic group on route and survey knowledge of the environment.

Route Distance-Estimation. This task is a magnitude-estimation task. Participants estimated the route distance between two locations. The participant was given a pair of room names and asked to provide a number equal to the length of the route between the two rooms, using the modulus as a standard for their estimates.

A difference score was calculated for the route distance estimates as follows: Route Distance Difference = Estimated Route Distance - Actual Route Distance. Positive difference scores indicate overestimates and negative difference scores indicate underestimates.

Direction Estimation. Participants were asked to estimate the direction (both elevation and azimuth) from one location to another location by pointing toward the target location.

As shown in the figure below, the azimuth estimates may range from 0 to 359.9 degrees. The elevation estimates may range from 0 to 180 degrees.

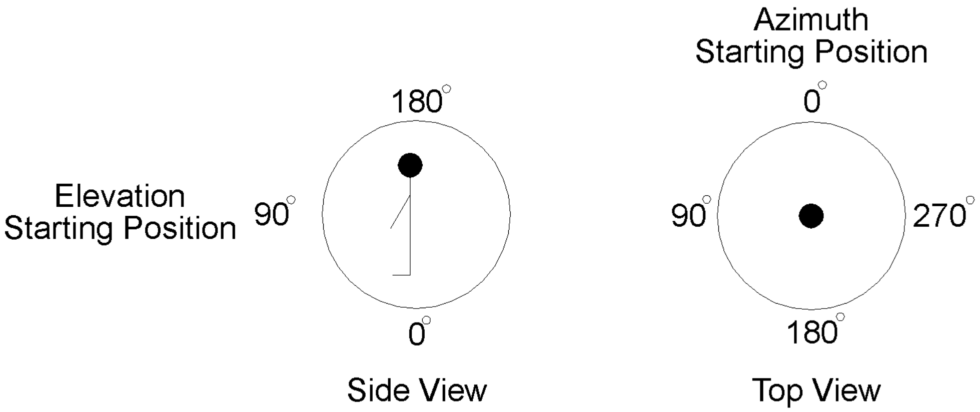


Figure 1. Azimuth and elevation directions in relation to participant’s virtual body position.

Azimuth difference scores were calculated as follows.

- When the target (i.e., true) azimuth is greater than or equal to 0 degrees and less than or equal to 180 degrees, Azimuth Difference = Estimated Azimuth - Actual Azimuth.
- When the target azimuth is greater than or equal to 180 degrees and less than 360 degrees, Azimuth Difference = Actual Azimuth - Estimated Azimuth.

A positive azimuth difference score indicates the estimated azimuth is farther from the start position (0^o) than the target azimuth.

Elevation difference scores were calculated using the following formula:

Elevation Difference = Estimated Elevation - Actual Elevation

A positive elevation difference score indicates the estimated elevation is above the actual elevation, i.e., the participant pointed above the target.

Room Location Decision RT. Participants were asked to decide whether a room is on the first or second floor. RT was measured.

Navigation Performance On Novel Routes. Participants were asked to travel between two rooms. Time to complete the route, number of errors, and the difference between route distance and shortest route distance were measured.

The table below shows the dependent variables for the learning trials and the post-learning assessment of environmental knowledge.

Table 5 Dependent Variables

	Learning Trials	Post-Learning
Time to complete route	x	x
Number of errors	x	x
Distance traveled	x	x
Distance traveled on wrong floor	x	x
Route distance estimate		x
Direction estimate		x
Room location decision		x

Participants

There were thirty participants. All the participants were undergraduate psychology students from the participant pool at North Carolina State University (NCSU). As participants in this study, those from the participant pool fulfilled part of their experiment participation requirements for Introductory Psychology. Eighteen of the participants were male. Twelve of the participants were female. The mean age was 20.57 years. More information about the participants and their responses to the pre-experiment questionnaire appears in the Results section.

Materials and Apparatus

Virtual Environment

The VE was built using Worldcraft software and Quake graphics engine. The software ran on a Pentium 166 MHz computer. Participants viewed the VE on a 20” television at a resolution of 400 pixels X 300 pixels. The television was an integrated TV-

VCR unit. The experimenter viewed the VE on a 17" computer monitor at a resolution of 400 pixels X 300 pixels. This monitor received the same video signal as the television viewed by the participant thereby allowing the experimenter to view the participant's movements in the VE. Participant's movement through the VE was videotaped using the integrated VCR. See Appendix A for a tour of the VE.

For this experiment, the characteristics of the VE and the participant's navigation are shown in the table below.

Table 6 Summary of VE Characteristics

Characteristic	**Level or Magnitude**
Horizontal Range of Field of Regard	360^0
Range of Angle of Declination	148^0 (-79^0 to 69^0)
Field of View	90^0 Horz X 60^0 Vert
Forward Speed	8 feet per second
Backward Speed	4 feet per second
Eye Height	Approximately 6 ft
Display Resolution	400 pixels X 300 pixels
Frame Rate	20 fps - 30 fps
Colors	256

Floorplan

As can be seen in the figure below, the VE is a two-story building. Each floor contains seven rooms which are labeled and serve as targets during navigation. The rooms were numbered to facilitate navigation. Rooms on the first floor were numbered 1-1 through 1-7. Rooms on the second floor were numbered 2-1 through 2-7.

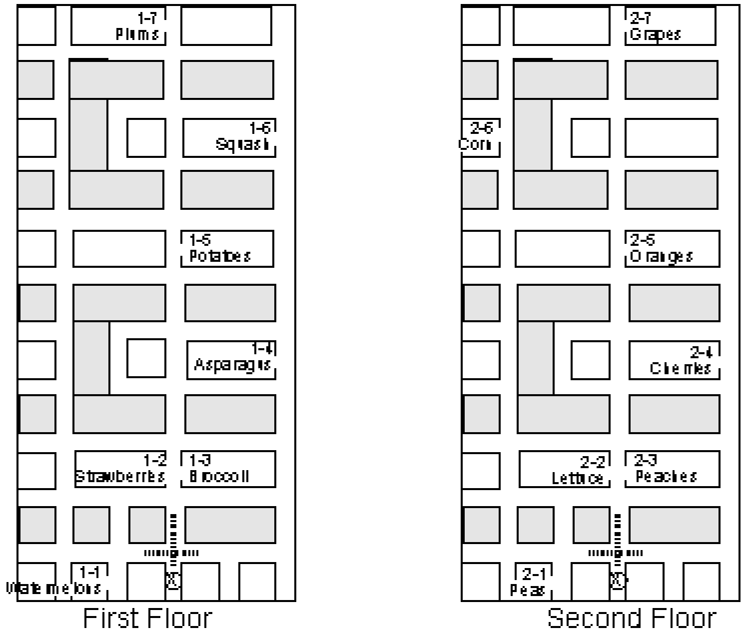


Figure 2. VE Floorplan

The overall dimensions of each floor are 183 feet 4 inches by 86 feet 6 inches. A stairway joins the first and second floors. There is a platform approximately 2/3 of the way up the stairs. From this platform, stairs lead straight ahead, to the right or to the left. The length of the stairs, the platform, and the turns in the stairs were designed so that the length of routes from the starting point to the second floor rooms are equal to the length of routes from the starting point to the first floor rooms, e.g., in Figure 2, ⊗ and Broccoli are on the first floor while Peaches is on the second floor. The distance from ⊗ to Broccoli is equal to the distance from ⊗ to Peaches. The figure below shows the view from the starting point at the bottom of the stairs. Although the figure appears in shades of gray, the VE appeared in 256 colors.

Figure 3. View from starting point in the virtual environment

The hallways are parallel to the cardinal axes. Diagonal movement between rooms is not possible. Hallways parallel to the long axis are approximately 5 feet 10 inches wide. Hallways parallel to the short axis are approximately 23 feet 4 inches wide. In the larger hallways on the first floor, the paths are created by the placement of large, low blocks. Participants can look across the blocks but cannot move across them. On the second floor, the larger hallways are divided into paths by openings in the floor. The openings are the same size and in the same location as the blocks on the first floor. Railings prevent participants from falling through these openings. Participants can see between floors through these openings.

Within a hallway, movement is restricted to a path approximately 70 inches wide. The width of the paths was chosen as a compromise between three factors. First, the path must be wide enough not to impede movement even if the direction of movement varies slightly while the participant moves down the path. Second, the path should be narrow enough that estimating the distance traveled can be achieved by measuring the straight line distance along the path. If the path is too wide, the participant could weave back and forth across the path. The software used to create VE does not have the capability to track the participant's path. If weaving back and forth across the hallway significantly increases the distance traveled, the straight line distance along the path would no longer be a useful estimate of the true distance traveled. Third, the path width should be similar to those found in the real-world so that the results of the experiment are more likely to be externally valid with regard to navigation and spatial knowledge of real-world environments.

Rooms

The seven rooms on each floor were labeled with the name of a fruit or vegetable. Prior to the construction of the VE, the experimenter asked nine people to list as many fruits and vegetables as possible. Frequency and order of recall were tabulated for the recall protocols of all nine people. The room names were those fruits and vegetables named most frequently and earliest in the list provided be each person.

The room names appear in the table below. The room names allow the addition of a semantic component to spatial knowledge of the VE.

Table 7 Room Names in the Virtual Environment

Fruit Names	**Vegetable Names**
Cherries	Asparagus
Grapes	Broccoli
Oranges	Corn
Peaches	Lettuce
Plums	Peas
Strawberries	Potatoes
Watermelons	Squash

On each floor, there is a hallway leading from the stairway to the other end of the building. Rooms in the same group appear on the same side of this hallway. As shown in Figure 2, there are 3 rooms in one group and four rooms of the other group on the first floor. On the second floor, there are four rooms in one group and three rooms in the other.

Joystick

Participants controlled movement through the VE with a Logitech Wingman Warrior joystick. Moving the joystick moves the participant's virtual body in the direction of the joystick without direction the body is facing. The participant must hold the joystick in the direction of movement. Releasing the joystick stops movement and returns the joystick to its default, no movement, position. For example, moving the joystick backwards is equivalent to walking backwards while still facing forwards. Moving the joystick forward is equivalent to walking forward.

The joystick has a knob, with 360^0 rotation, for changing the azimuth of the field of regard. Turning the azimuth knob rotates the participant's view of the VE. Turning the azimuth knob counterclockwise turns the view to the left. Turning the azimuth knob clockwise turns the view to the right. This rotation is equivalent to rotating the participant's virtual body about an axis defined by the intersection of the transverse horizontal, coronal frontal, and midsagittal planes. Turning the azimuth knob does not move the participant from the participant's location. The azimuth knob is not spring-loaded. When the participant releases the azimuth knob, it remains in position and the view remains in the direction in which it was last pointed.

A thumb, or "hat", switch controls the elevation of the field of regard. Moving the thumb switch raises and lowers the participant's view by moving the participant's virtual head in the midsagittal plane. This movement is equivalent to changing the angle formed by the intersection of the Frankfurt Plane and the transverse horizontal plane. The Frankfurt Plane is the plane defined by a line passing through the right tragion (part of the ear) and the right eye socket. Moving the thumb switch down lowers the participant's view, i.e., the participant looks up. Moving the thumb switch up raises the participant's view, i.e., the participant looks down. The thumb switch is spring-loaded to return to center when it is released. However, the angle of inclination/declination does not change immediately when the switch is released. If the participant changes the angle of inclination/declination, the participant must move the switch or move forward or backward to return the angle to its default setting. The elevation switch was disabled during navigation. It was only be enabled for the collection of direction estimates.

The joystick has four other buttons and a thumb wheel. Two of the buttons were used by the participant, during navigation trials, to indicate they had arrived at the target room. Pressing either of these buttons causes the participant's virtual body to "jump." The "jump" provides a visual indication on the videotape that the participant has arrived at the target. The other two buttons were disabled during this study. Pressing the remaining two buttons or turning the thumb wheel had no effect on the participant's movement in the VE or view of the VE.

Crosshair

To assist the participant in moving and turning their virtual body, a small crosshair appears at the eye point along the midsagittal plane. This point is the center of the FOV. It represents the point toward which the virtual body will move, in a straight line, when the joystick is pushed forward. Pulling the joystick backward moves the body backwards, along the same line, away from the point. Moving the joystick to the right or left moves the body in a line perpendicular to the forward/backward line. Observation of people using this environment suggests that the crosshair helps people reduce their deviation in movement along the desired path. Ruddle, Payne, and Jones (1997) used a similar feature in their virtual environment.

Procedure

The experimenter told the participant that the participant would be asked to learn the layout of the virtual environment and would be tested on their knowledge of the environment. The participant would then be asked to read and sign an informed consent form. The informed consent form and all other experimental materials appear in Appendix A.

After signing the form, each participant completed the following activities: (a) Familiarization with the VE, (b) Train with the joystick in the VE, (c) Learn the environment, (d) Test of knowledge of the environment, (e) Debrief.

The following sections describe each of these activities in more detail.

Familiarization with the VE

One problem with studying human behavior in virtual environments is the novelty of the appearance of the environment and the rules governing movement in the environment. The first two steps in the experimental procedure are designed to reduce the influence of these new experiences. The VE used in these steps was similar in appearance but different in layout from the experimental VE. The floorplan of the practice environment is shown in the figure below.

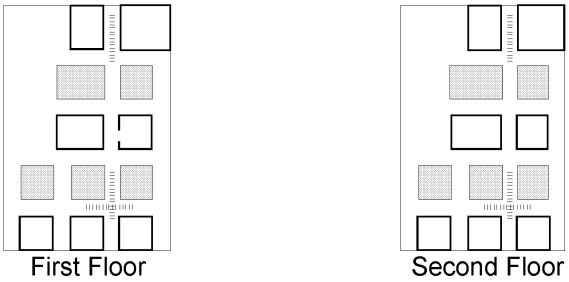


Figure 4. Practice Environment Floorplan

The first step is to show the participant the characteristics of the VE that may affect navigation in and memory for the environment. These characteristics include stairs, doors, textures, ledges and objects in the environment. Each participant viewed 1 minute of a demonstration of the VE by the experimenter before proceeding to joystick training.

Training with the Joystick in the VE

During the demonstration, the experimenter described how moving the joystick moves the participant through the VE. Following familiarization with the VE, the participant practiced moving through the VE by manipulating the joystick and azimuth knob. The participant practiced the following actions: (a) moving forward, (b) moving backward, (c) turning without moving, (d) turning while moving, (e) moving up and down stairs. During joystick training, the participant followed a path through the practice environment. Upon reaching the start-end point of the path, the participant reversed direction and followed the path in the opposite direction. The participant completed two circuits of the path in each direction.

Learning the Environment

The participant learned the layout of the VE by traveling a series of routes. The routes were designed to cross the three independent variables: Distance, Turns, and Floor. Each route began or ended at a neutral, i.e., non-fruit, non-vegetable, location on the first floor. The neutral location is marked by the ⊗ in Figure 2. When traveling to a room, the participant was given the room name and number and told to go to the destination as quickly as possible, i.e., follow the shortest route. When returning from the room to the starting point, participants were told to return to the bottom of the stairs.

There were six blocks of 14 learning trials. Within a block, each room appears once. In the first two blocks, the participant was given the room name and number. In the last four blocks, the participant was given the room name only. Six lists of room names were created.

Each list contains the same room names but the order of presentation of rooms was randomized within each list. Each participant got all six lists. The order of presentation of lists was randomized for each participant.

The table below shows the combination of the three independent variables for each of the start point-to-room routes.

Table 8 Route Distance, Turns, and Floor for Learning Trials.

Destination Room	**Route Distance**	**Route Turns**	**Floor**
Broccoli	32 feet 2 inches	0	1
Asparagus	108 feet 6 inches	2	1
Potatoes	108 feet 6 inches	0	1
Squash	180 feet 10 inches	2	1
Peas	32 feet 2 inches	2	2
Lettuce	32 feet 2 inches	0	2
Corn	180 feet 10 inches	2	2
Watermelons	32 feet 2 inches	2	1
Strawberries	32 feet 2 inches	0	1
Plums	180 feet 10 inches	0	1
Peaches	32 feet 2 inches	0	2
Cherries	108 feet 6 inches	2	2
Oranges	108 feet 6 inches	0	2
Grapes	180 feet 10 inches	2	2

Tests of Knowledge of the Virtual Environment

There were four tests of knowledge of the VE: route distance-estimation, direction estimation, room location decision, and navigation. The first two tests assess both route and survey knowledge. The order of presentation of the first three tests were counterbalanced. The navigation test was always performed last because some of the origin-target pairs used in the distance estimates, direction estimates, and room location decisions are intended to assess survey knowledge of the environment. If the navigation test were administered prior to the other tests, there would be no tests of survey knowledge. The following sections describe the procedure for obtaining each of these measures.

Route Distance-Estimation. Before making any estimates, participants were shown a route to be used as the modulus. The modulus route was a straight route, 108 feet 6 inches in length. The modulus distance was selected because of its proximity to the middle of the range of distances between rooms in the VE (Poulton, 1968). The experimenter traveled the route once in each direction. The experimenter told the participant that the route distance is equivalent to a length of 100 and the unit of measurement would not be provided.

Thirty origin-target pairs were created. All 14 of the routes used during the learning trials formed origin-target pairs for the route distance-estimation task. Each room served as a target. The participant was asked to estimate the route distance for routes that were not used during the learning trials. There were 16 origin-target pairs for the new routes. The 16 pairs cross the four independent variables route distance (868 and 1736 inches), route turns (0 or 2), floor (same floor or different floor), and group (same group or different group). The pairs were formed so that: (a) half of the same-floor routes are on the first floor and half are on the second floor; (b) half of the same-group routes are in the fruit group and half are in the vegetable group. For each pair, the participant was asked to imagine being at the origin and to estimate the route distance to the target. The participant entered the estimate in a Microsoft Access form.

One block of origin-target pairs was created. The learning trial pairs (neutral point-room) and the new route pairs (room-room) were mixed together in a random order.

Direction Estimation. In the direction estimation task, participants estimated the direction from one location to another. On each trial, the participant was placed in front of an unlabeled door or a set of stairs identical to the stairs at the starting point in the VE. They were told to imagine they are in front of one of the rooms or at the starting point at the base of the stairs. They were asked to point the crosshair in the direction of the target room. The participant began each trial facing the same direction and with the crosshair pointing parallel to the floor. Both azimuth and elevation angle were measured on each trial. The origin-target pairs used in the route distance-estimation task were used for this task.

Room Location Decision. In the room location decision task, two rooms, a prime and a target, were presented on each trial. The participant was asked to decide whether the target is on the same or different floor as the prime. Prime-target pairs are the same room-room pairs used for the route distance-estimation task. The neutral-room pairs were not used for this task.

The participant started each trial by pressing the space bar. One second later, a fixation marker appeared near the center of the screen. The fixation marker remained visible for 250 msec followed by a blank screen for 250 msec. The prime appeared next for 200 msec followed by a blank screen for 50 msec. The target then appeared and remained visible until the participant responded. The participant pressed the F key if the target was on the same floor and the J key if the target was on a different floor. Between trials, participants placed their fingers on the F and J keys. The instructions emphasized that the participant should try to attain 95% accuracy in their responses while responding as quickly as possible.

Novel Route Navigation. In the navigation task, the participant was placed at the entrance to a room and was asked to travel to another room. The 16 room-room pairs used in the route distance-estimation task, were used as test pairs in this task.

Results

Overview

This section describes the results of the participant questionnaire, learning trials, and post-learning measures. The results of the participant questionnaire appear in the first section. The frequency of responses to the questions are presented in a series of tables. No analysis was performed on the questionnaire data.

In the second section, the results of the learning trials analysis appear. In the learning trials, participants navigated from a starting point to a target room and then returned to the starting point. Target room locations were defined by a factorial crossing of Distance (3 levels), Turns (2 levels), and Floor (2 levels). Several measures of navigation performance were collected during the navigation to and from a target room. The data were analyzed using a MANOVA to assess the multivariate significance of the main effects and interactions. Those effects that were significant, using the multivariate criterion, were analyzed using separate ANOVAs for each dependent variable. If the ANOVA was significant and the effect involved more than two groups, the significance of the difference between groups was assessed using Tukey’s HSD.

Participant Questionnaire

Prior to learning the VE, the participants completed a questionnaire designed to collect demographic information and assess the participant's experience with computer games and virtual environments. The following tables summarize the responses to the questionnaire.

Table 9 Participant Gender

	Gender
Male	18
Female	12

Table 10 Participant Age

Age (years)	
Mean	20.57
Standard Deviation	3.81
Minimum	18
Maximum	34
Mode	18

Table 11 Participant Year in School

Year in school	
Freshman	15
Sophomore	7
Junior	4
Senior	1
Other	3

Table 12 Participant Self-Assessment of Sense of Direction

How do you believe your sense of direction compares with that of other people's sense of direction?	
My sense of direction is below average.	0
My sense of direction is average.	22
My sense of direction is above average.	8

Table 13 Frequency of Computer Use

How often do you use a computer?	
Every day	17
Every other day	5
Once or twice a week	8
Once or twice every few weeks	0
Once or twice a month	0

Table 14 Prior Joystick Use

Have you ever used a joystick?	
Yes	28
No	2

Table 15 Wingman Warrior Joystick Use

Have you ever used the joystick you will use in this experiment?	
Yes	1
No	29

Table 16 Computer Game Experience

Have you ever played a computer game other than those that are part of MS Windows?	
Yes	27
No	3

Table 17 First-Person Computer Game Experience

Have you ever played a first-person computer game, e.g., Doom, Quake, Descent?	
Yes	14
No	16

Table 18 Computer Game Frequency

How often do you play computer games?	
Every day	3
Every other day	2
Once or twice a week	9
Once or twice every few weeks	5
Once or twice a month	11
Never	0

After the data from the learning trials were screened for outliers, the relationship between the participants' questionnaire responses and the dependent measures was examined. Tables 23, 24 and 45, which follow the discussion of data screening, show the correlations between the dependent measures and the questionnaire responses. None of the correlations was high enough to justify inclusion in the analyses as a covariate.

Learning Trials

Participants completed six learning trials for each of the 14 rooms in the VE, i.e., each participant completed 84 learning trials. In each trial participants traveled to a room and back. They were instructed to find the shortest route to the room and back again. Four measures of navigation performance were collected during each trial: POD, POT, PPE, and EED.

The analyses described in the following paragraphs, use only the data from the first five trials. All participants learned the location of all rooms by the sixth trial. There is no variance in POT, PPE, and EED because the participants traveled the shortest route, with no errors, to all the rooms and back. This means neither the multivariate nor univariate F can be computed because calculation of the F statistic would require division by zero.

Data Screening

POT was originally intended to help discriminate between trials in which participants moved continuously toward a target and trials in which the participant paused while searching for a target. In either case, if the participant traveled the shortest path to the target, POD would be equal. Yet POT would be greater in those trials in which the participant paused- ostensibly to make a decision about the location of the target and the shortest route to it. Unfortunately, during the experiment, it was apparent that POT was as much a measure of skill with the joystick as it was a measure of knowledge of room location. Based on the experimenter’s observations, the time required to reach a target room or return to the starting point was often equally dependent on joystick skill and knowledge of room location. In no instance did participant's turn the wrong way or miss a turn they had intended to take. However, they frequently ran into walls and stairs which required them to move backward and turn slightly before continuing. In consideration of the intent of POT and the difficulty in interpreting its real meaning, POT was dropped from the analysis.

The data collected during the learning trials were separated into "Out" and "Back" data. The Out data contained the data obtained while the participant was traveling from the starting point to the target room. The Back data contained the data obtained while the participant traveled from the target room back to the starting point. The histograms below show the differences in the distribution of scores for the Out and Back legs of each trial. The table below shows the correlations between the scores for Out and Back legs. There appears to be no relationship between a participant's ability to find a target room and their ability to find their way back to the starting point.

Table 19 Correlation Between Out Data and Back Data

	POD	EED
POD	0.04	
EED		-0.01

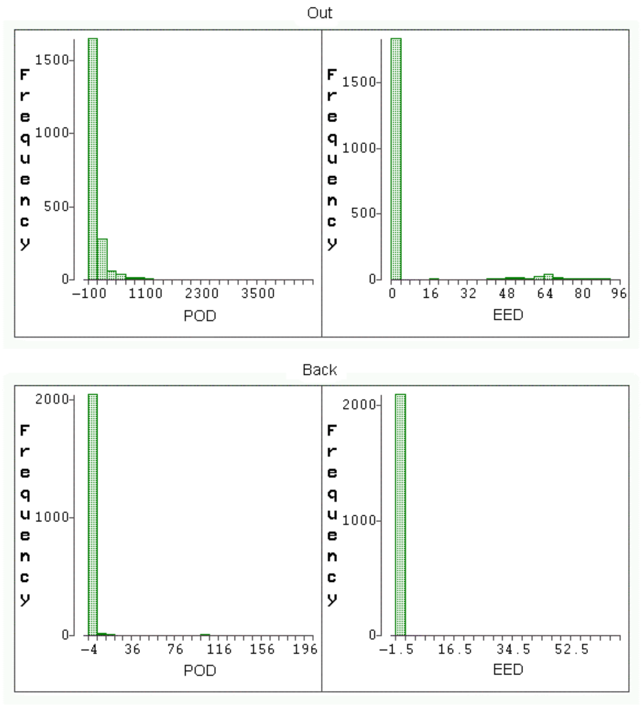


Figure 5. Distribution of raw POD and EED Out Data and Back data.

Prior to analyzing the data with a MANOVA the correlations between the remaining dependent measures were calculated for the Out and Back data. If the dependent measures are highly correlated, then they are probably measuring the same construct. In this situation, only one DV should be used in the analysis to avoid the problems associated with multicollinearity. If the DVs are not correlated, separate ANOVAs would provide a more powerful analysis. DVs with moderate correlations would be candidates for a MANOVA. The correlations appear in the tables below.

As shown by the high positive correlation between POD and PPE, it appears as if POD and PPE are measuring the same part of the same construct. At this point in the analysis, this construct might be called “knowledge of the target room’s location.” There is little benefit in keeping both POD and PPE in the MANOVA. In contrast, POD and PPE are moderately correlated with EED. EED is measuring something similar but slightly different. The construct being measured might be called “knowledge of the floor containing the target room.” Since MANOVA works best with moderately correlated DVs, keeping EED and either POD or PPE would produce the most useful analysis.

Table 20 Correlations Between Dependent Variables for Out Data

	POD	PPE
POD		
PPE	0.95	
EED	0.43	0.49

Table 21 Correlations Between Dependent Variables for Back Data

	POD	PPE
POD		
PPE	0.86	
EED	.	.

Note: EED was 0 for all routes in all trials.

POD was chosen instead of PPE for ease of interpretation. It is easier to understand "The participants traveled an average of 30% farther than the optimal route..." than to understand "The percentage of possible errors was 110% on this route..." For the remaining analysis of the learning trials, only POD and EED are discussed. As described by the note in the table above, EED was not used in the analysis of the Back data because EED was 0 for all routes in all trials, i.e., there were no elevation errors when the participants returned to the starting point from the target room.

Before analyzing the Out or Back data, POD and EED were screened for univariate and multivariate outliers. The POD and EED raw scores were standardized. The figure below shows the distribution and means for the standardized POD and EED data. The absence of a box, diamond, or outliers for EED on Back legs shows that there were no floor errors when subjects were traveling from the target room to the starting point. (See Appendix A for a brief introduction to the interpretation of box plots.)

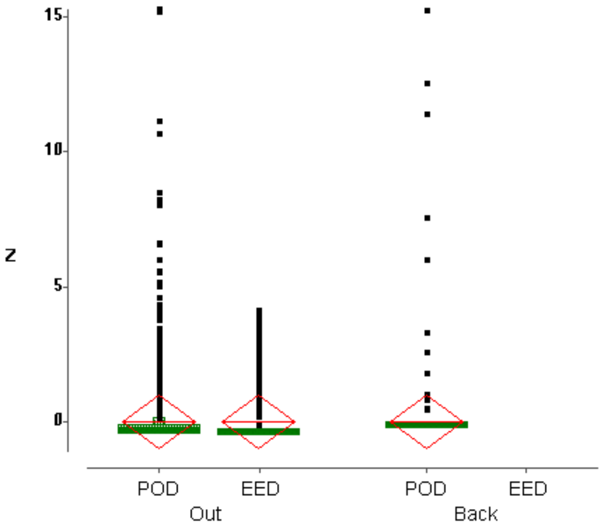


Figure 6. Distribution and means of standardized POD and EED for Out Data and Back data

Visual inspection of the data can provide insight into the nature of univariate and multivariate outliers. The figure below shows a scatterplot of the standardized POD and EED Out data. The triangles are univariate POD outliers. The circles are univariate EED outliers. The crosses are multivariate outliers. The observations inside the box are the observations used in subsequent analyses. The observations outside the box are univariate or multivariate outliers.

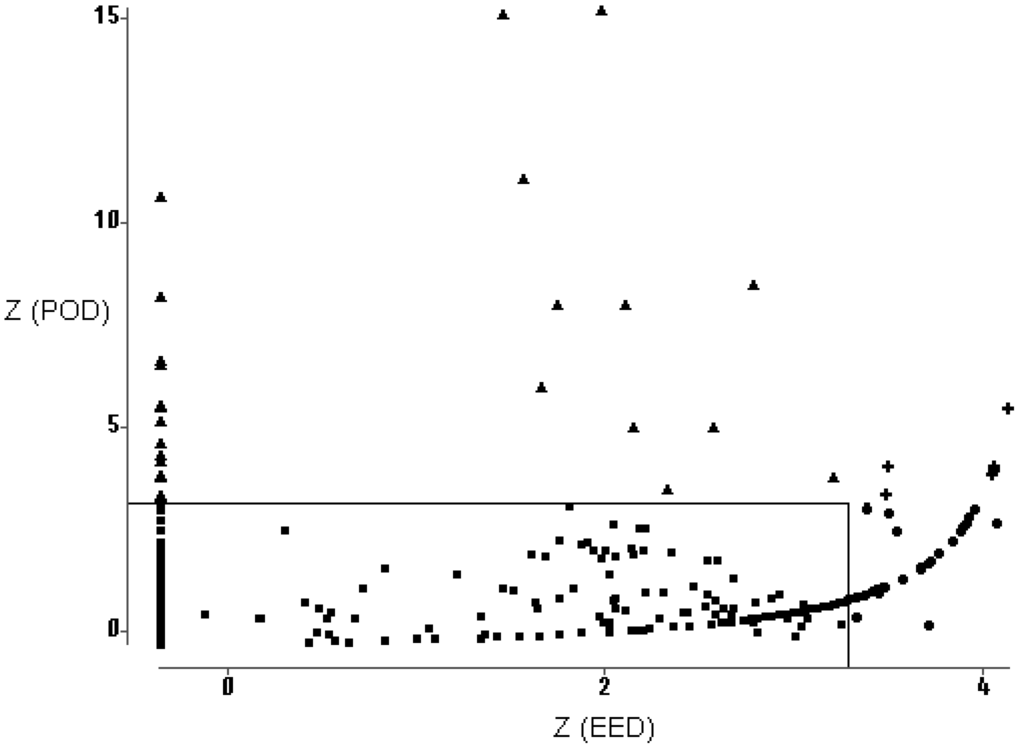


Figure 7. Scatter plot of standardized POD and EED scores for Out data

In the Out trials, large individual differences were observed when examining the data for outliers. As shown in the figure below, several participants experienced greater difficulty in finding the target room. Participants 7, 8, 9, and 16 traveled farther than most other participants while searching for the target room. The figure below also suggests that participants 7 and 16 were more likely to travel farther on the wrong floor while searching for the target room.

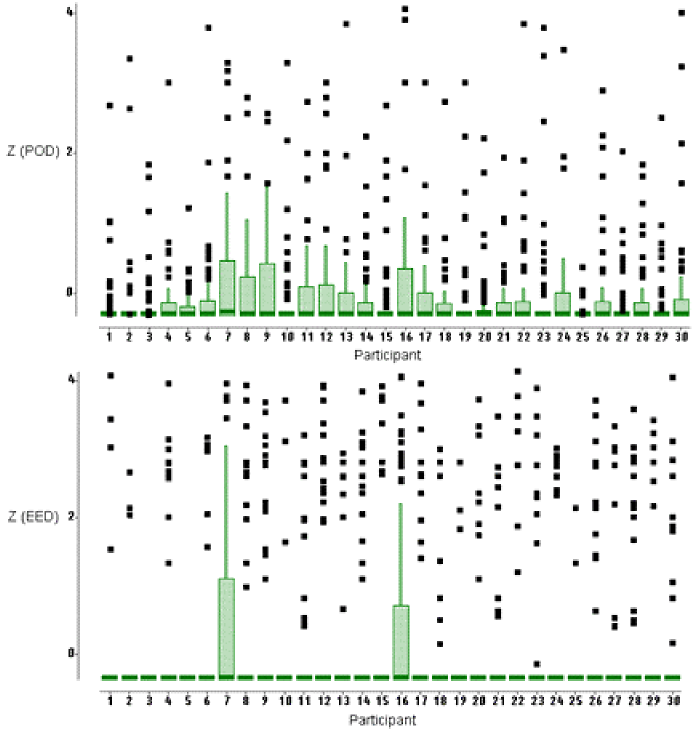


Figure 8. Distribution and means of standardized POD and EED by subject for Out legs

Tabachnik and Fidell (1996) suggest standardizing the dependent measures and examining those whose standardized scores exceed 3.29. The table below summarizes the range of standardized scores for each dependent measure. Seventy three observations were removed from the Out data. Sixteen observations were removed from the Back data.

Table 22 POD and EED Outliers Using a Standardized Score of 3.29 as a Cutoff

Direction	Out		Back	
	Dependent Measure			
	POD	EED	POD	EED
Minimum	-0.31	-0.36	-0.11	0
Maximum	15.29	4.16	15.54	0
Median	-0.31	-0.36	-0.11	0
Number of univariate outliers	27	38	16	0
Total number of outliers	33	44	16	0

After screening the POD and EED data for outliers, the normality of the distribution of each variable was assessed. The table below contains the mean, standard deviation, skewness and kurtosis for the two distributions for Out and Back data. With the exception of the Back - EED distribution, the distributions are skewed to the right.

Table 23 Distributions of Raw POD and EED Data

	Out		Back	
	POD	EED	POD	EED
Mean	52.51	5.60	0.20	0
Std Dev	130.11	17.42	1.69	0
Skewness	3.80	2.98	9.37	.
Kurtosis	17.62	7.27	93.52	.

To reduce the amount of skewness and kurtosis, the data were transformed by taking the square root of the raw POD and EED scores. The table below describes the distribution of the transformed variables.

Table 24 Distribution of Transformed (square root) POD and EED Data

	Out		Back	
	POD	EED	POD	EED
Mean	3.39	0.75	0.06	0
Std Dev	6.41	2.25	0.44	0
Skewness	1.89	2.76	8.17	.
Kurtosis	2.95	5.83	67.29	.

Relationship Between Dependent Measures and Participant Characteristics

The participant questionnaire was designed to assess the participant's experience with computers and computer games. If any of these characteristics were moderately or strongly correlated with the dependent measures, they could have been treated as covariates in the analyses. As shown in the following tables, there was a non-existent to weak relationship between the responses to the participant questionnaire and the dependent measures. None of these characteristics was used as a covariate.

Table 25 Correlations Between Participant Characteristics and Dependent Measures for Out Data in Learning Trials

	Dependent Measure	
Participant Characteristic	POD	EED
Gender	0.0236	0.0044
Age	-0.0128	-0.0144
Year in School	-0.0237	-0.0479
Sense of Direction	-0.0542	-0.0074
Computer Use	-0.0064	-0.0035
Joystick Use	-0.1030	-0.0567
Wingman Use	-0.0021	0.0407
Game Experience	-0.0402	-0.0498
FP Game Experience	-0.0624	-0.0120
Game Frequency	0.0455	0.0608

Table 26 Correlations Between Participant Characteristics and Dependent Measures for Back Data in Learning Trials

	Dependent Measure	
Participant Characteristic	POD	EED
Gender	0.0873	.
Age	0.1240	.
Year in School	-0.0102	.
Sense of Direction	0.0519	.
Computer Use	0.0856	.
Joystick Use	0.0126	.
Wingman Use	-0.0221	.
Game Experience	0.0142	.
FP Game Experience	-0.0383	.
Game Frequency	-0.0058	.

Note: EED was 0 for all routes in all trials.

MANOVA Analysis of the Out Data for Trials 1 - 5

The Out data were analyzed using a MANOVA with Trial, Distance, Turns, Floor, and Order as independent variables. Order was the random order in which target rooms were presented to participants. The main effects, 2-way, and 3-way interactions were tested for Distance, Turns, Floor, and Order. Only the main effect of Trial was tested in this analysis. A follow-up analysis was planned, if the main effect of Trial was significant, to assess the change in navigation performance across trials.

The table below summarizes the results of the MANOVA. Wilks' Lambda was used as the multivariate test criterion. The main effects of Trial, Distance, Turns, and Floor were significant at p = .01. The 2-way interactions and 3-way interactions were also significant.

Table 27 MANOVA Test Criterion and F Approximations for Trials 1 - 5

Effect	Wilks' Lambda	F	Num df	Den df	Pr > F
Trial	0.16	43.68	8	230	0.0001
Distance	0.51	9.28	4	94	0.0001
Turns	0.15	65.23	2	23	0.0001
Floor	0.21	43.99	2	23	0.0001
Distance x Turns	0.80	2.74	4	94	0.0328
Distance x Floor	0.55	8.26	4	94	0.0001
Turns x Floor	0.34	22.51	2	23	0.0001
Distance x Turns x Floor	0.72	5.06	4	114	0.0009
Order	0.62	1.23	10	46	0.3005
Order x Distance	0.86	0.38	20	94	0.9903
Order x Turns	0.76	0.67	10	46	0.7489
Order x Floor	0.61	1.31	10	46	0.2520
Order x Distance x Turns	0.69	0.96	20	94	0.5257
Order x Distance x Floor	0.85	0.40	20	94	0.9946
Order x Turns x Floor	0.73	0.79	10	46	0.6474

For the significant multivariate tests, univariate ANOVAs, one for each dependent variable, were performed to test the influence of the independent variables on the dependent measures separately. The table below shows the results of the ANOVAs.

Table 28 ANOVA Results for Effects That were Significant Using the Multivariate Criterion

Effect	Dependent Measure	F	Num DF	Den DF	Pr > F
Trial	POD	29.44	4	116	0.0001
	EED	35.46	4	116	0.0001
Distance	POD	14.78	2	48	0.0001
	EED	16.60	2	48	0.0001
Turns	POD	73.15	1	24	0.0001
	EED	0.34	1	24	0.5666
Floor	POD	0.03	1	24	0.8794
	EED	32.23	1	24	0.0001
Distance x Turns	POD	4.43	2	48	0.0215
	EED	1.16	2	48	0.3284
Distance x Floor	POD	15.55	2	48	0.0001
	EED	12.35	2	48	0.0001
Turns x Floor	POD	30.71	1	24	0.0001
	EED	2.41	1	24	0.1357
Distance x Turns x Floor	POD	8.09	2	58	0.0008
	EED	8.13	2	58	0.0008

All but four of the univariate tests were significant. The main effect of Turns, the Distance x Turns interaction, and the Turns x Floor interaction were not significant with EED as a dependent variable. The main effect of Floor was not significant with POD as the dependent variable.

Further analyses were run to identify significant differences among the means for the Trial main effect, Distance main effect and the interactions. In all analyses, unless explicitly described otherwise, Tukey's HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at $\underline{p} < .05$.

The results of the comparisons among POD means and comparisons among EED means for the Trial main effect are shown in the tables below. POD and EED were greatest for Trial 3. POD was least for Trial 5. EED was least for Trials 1 and 2.

Table 29 Significant Differences Among Trial POD Means.

Trial	Mean			
3	5.35	a		
1	4.59	a		
4	3.21		b	
2	2.37		b	c
5	1.57			c

Note: Trials with the same letter are not significantly different.

Table 30 Significant Differences Among Trial EED Means.

Trial	Mean		
3	1.88		
4	1.15		
5	0.62	a	
1	0.12	a	b
2	0.05		b

Note: Trials with the same letter are not significantly different.

Figures 9 and 10 show the Trial means for POD and EED.

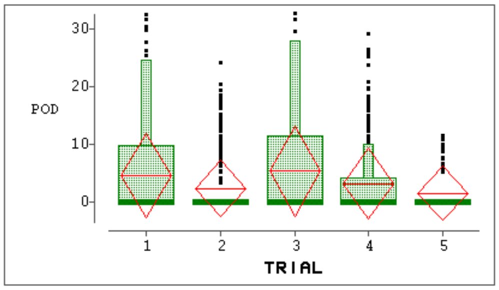


Figure 9. POD as a function of Trial for trials 1-5

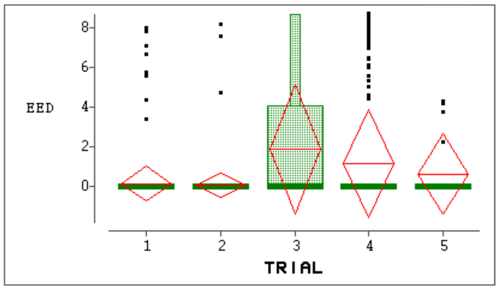


Figure 10. EED as a function of Trial for trials 1 - 5

For the main effect of Distance, the difference between the short distance (POD M = 2.14, EED M = 0.37) and the two other distances (POD M = 4.68, EED M = 1.04) (POD M = 3.89, EED M = 0.99) was significant for POD and EED. Figures 11 and 12 show the POD and EED means for Distance.

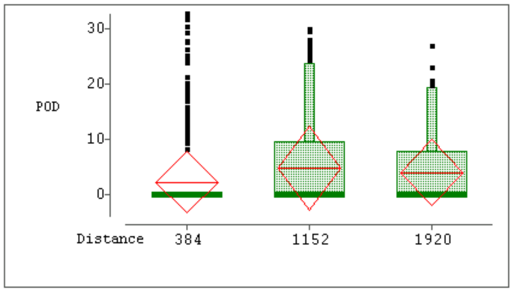


Figure 11. POD as a function of Distance for trials 1-5.

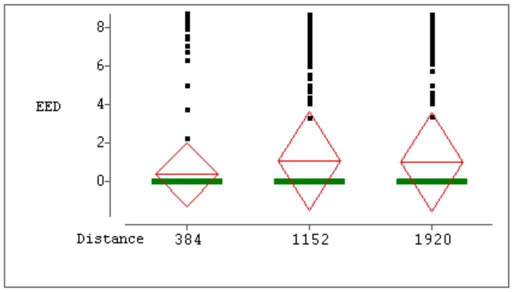


Figure 12. EED as a function of Distance for trials 1 - 5

For the main effect of Turns, POD was significantly greater for routes with 2 turns (M = 5.71) than for routes with 0 turns (M = 1.65). Figure 13 shows the Turns POD means.

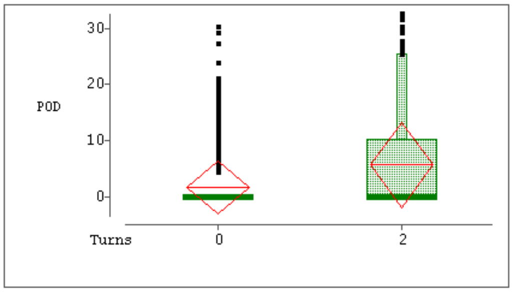


Figure 13. POD as a function of Turns for trials 1 - 5

For the main effect of Floor, EED was significantly greater for first floor routes (M = 1.00) than for second floor routes (M = 0.49). Figure 14 shows the Floor EED means.

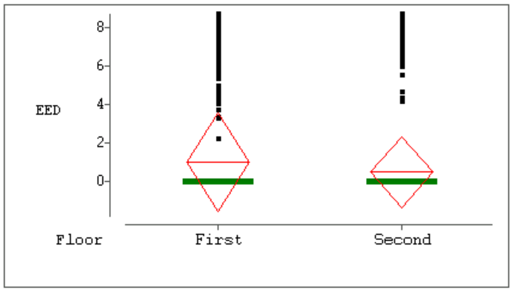


Figure 14. EED as a function of Floor for trials 1 - 5

Figure 15 shows the POD distributions and means for the Distance x Turns interaction. Two sets of comparisons were made between the means. In the first comparison, means for the 0-turn and 2-turn routes were compared within each distance. For all distances, POD for 2-turn routes (M = 4.10) (M = 7.15) (M = 5.78) was significantly greater than POD for 0-turn routes (M =1.19) (M = 2.18) (M = 2.01). In the second comparison, means for each distance were compared within 0-turn and 2-turn routes. For 0-turn routes, POD for the shortest distance (M =1.19) was significantly less than POD for the medium distance (M = 2.18). For 2-turn routes, POD for the shortest distance (M = 4.10) was significantly less than POD for the other two distances (M = 7.15) (M = 5.78).

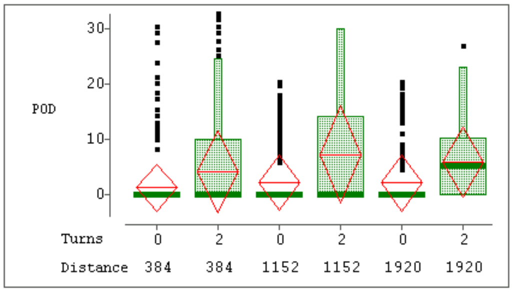


Figure 15. POD as a function of Distance and Turns for trials 1 - 5

Figure 16 shows the POD distributions and means for the Distance x Floor interaction. Two sets of comparisons were made between the means. In the first comparison, means for the first and second floor routes were compared within each distance. For the shortest distance, the difference between first and second floor routes was not significant. For the middle distance, POD for second floor routes (M = 5.24) was significantly greater than POD for first floor routes (M = 4.12). For the longest distance, POD for second floor routes (M = 2.92) was significantly less than POD for first floor routes (M = 4.86). In the second comparison, means for each distance were compared within first floor and second floor routes. For first floor routes, POD for the longest distance (M = 4.86) was significantly greater than POD for the other two distances. POD for the middle distance (M = 4.12) was significantly greater than POD for the shortest distance (M = 2.00). For second floor routes, POD for the middle distance (M = 5.24) was significantly greater than POD for the other two distances (M = 2.28) (M = 2.92).

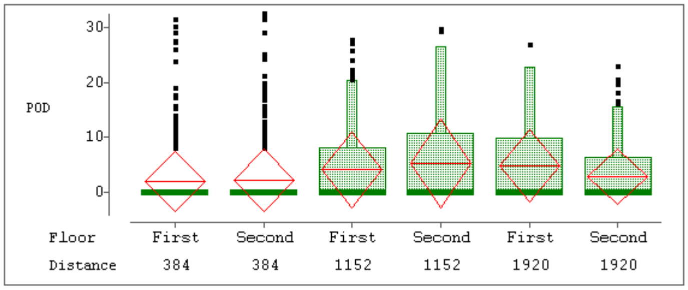


Figure 16. POD as a function of Distance and Floor for trials 1 - 5

Figure 17 shows the EED distributions and means for the Distance x Floor interaction. The same set of comparisons, made between the POD means, was made between the EED means to assess the nature of the Distance x Floor interaction. In the first comparison, means for the first and second floor routes were compared within each distance. For the shortest (M = 0.49) and longest distances (M = 1.56), EED for first floor routes was significantly greater than EED for second floor routes (M = 0.25) (M = 0.43). For the middle distance, the difference between first and second floor routes was not significant. In the second comparison, means for each distance were compared within first floor and second floor routes. For first floor routes, EED for the longest distance (M = 1.56) was significantly greater than EED for the other two distances. EED for the middle distance (M = 1.18) was significantly greater than EED for the shortest distance (M = 0.49). For second floor routes, EED for the middle distance (M = 0.89) was significantly greater than EED for the other two distances (M = 0.25) (M = 0.43).

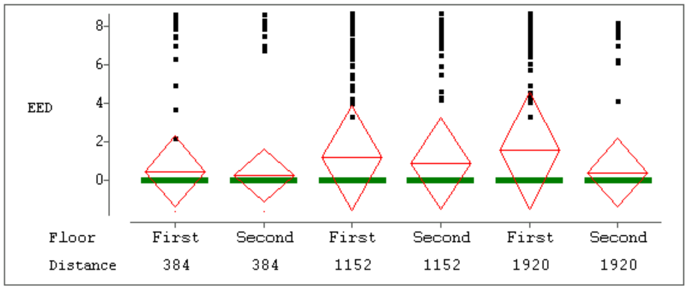


Figure 17. EED as a function of Distance and Floor for trials 1 - 5

Figure 18 shows the POD distributions and means for the Turns x Floor interaction. Two sets of comparisons were made between the means. In the first comparison, means for the 0-turn and 2-turn routes were compared within each floor. For both first (M = 4.99) and second floor (M = 6.45) routes, POD for 2-turn routes was significantly greater than POD for 0-turn routes (M = 2.27) (M = 1.03). In the second comparison, means for each floor were compared within 0-turn and 2-turn routes. For 0-turn routes, POD for the second floor routes (M = 1.03) was significantly less than POD for first floor routes (M = 2.27). For 2-turn routes, POD for the second floor routes (M = 6.45) was significantly greater than POD for first floor routes (M =4.99).

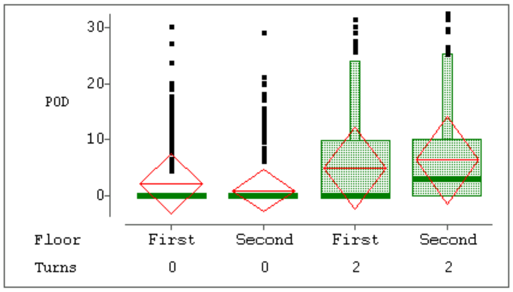


Figure 18. POD as function of Turns and Floor for trials 1 - 5

Figures 19 and 20 show the POD and EED distribution and means for the Distance x Turns x Floor interaction. Three sets of comparisons were made for the POD means. In the first, means for each distance were compared within 0-turn and 2-turn routes within each floor. On first floor 0-turn routes, POD for the middle distance (M = 3.10) was significantly greater than POD for the shortest distance (M = 1.49). For 2-turn routes, POD for the longest distance (M = 6.81) was significantly greater than POD for the middle (M = 5.13) and shortest distance (M = 2.99). POD for the middle distance was significantly greater than POD for the shortest distance.

On the second floor, there were no significant differences among the distance means for 0-turn routes. For 2-turn routes, middle distance POD (M = 9.18) was significantly greater than the longest (M = 4.75) and shortest distance POD (M = 5.32).

In the second set of comparisons, means for 0-turn and 2-turn routes were compared within each distance and within each floor. For all distances on both floors, the 0-turn route POD was significantly less than the 2-turn route PODs.

In the third set of comparisons, means for the first and second floor routes were compared within each distance and within 0-turn and 2-turn routes. At the shortest distance and 0-turns, the difference between floors was not significant. At 2-turns, POD was greater for the second floor (M = 5.32) than for the first floor (M = 2.99). At the middle distance, the first floor POD mean (M = 3.10) was greater than the second floor POD mean (M = 1.25) for 0-turn routes. For 2-turn routes, the first floor POD mean (M = 5.13) was significantly less than the second floor POD mean (M = 9.18). At the longest distance, the first floor POD mean (M = 2.92) (M = 6.81) was greater than the second floor POD mean (M = 1.09) (M = 4.75) for both 0-turn and 2-turn routes.

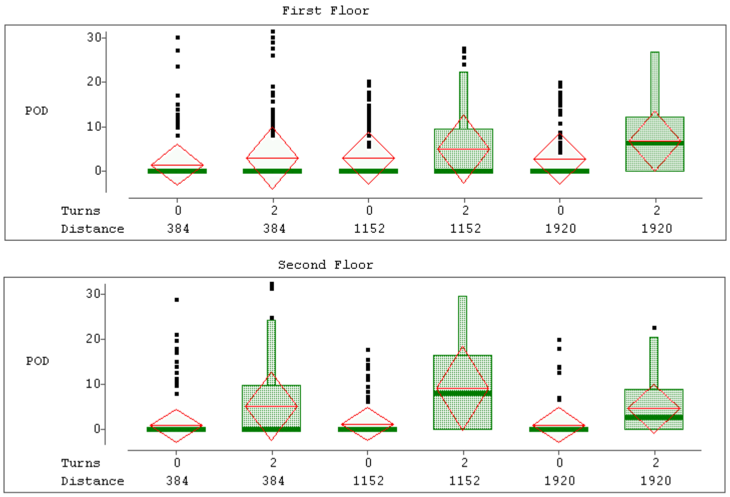


Figure 19. POD as a function of Distance, Turns, and Floor for trials 1 - 5

Three sets of comparisons were made for the EED means. In the first, means for each distance were compared within 0-turn and 2-turn routes within each floor. On first floor 0-turn routes, EED for the longest distance (M = 1.42) was significantly greater than EED for the shortest distance (M =0.53). For 2-turn routes, EED for the longest distance (M = 1.71) was significantly greater than EED for the middle distance (M = 0.79). EED for the middle distance was significantly greater than EED for the shortest distance (M = 0.40).

On the second floor, there were no significant differences among the distance means for 0-turn routes. For 2-turn routes, middle distance EED (M = 1.28) was significantly greater than the longest (M = 0.32) and shortest distance (M = 0.11) EED.

In the second set of comparisons, means for 0-turn and 2-turn routes were compared within each distance and within each floor. The only significant difference was for first floor middle distance routes. EED for 0 turns (M = 1.58) was significantly greater than EED for 2 turns (M = 0.79).

In the third set of comparisons, means for the first and second floor routes were compared within each distance and within 0-turn and 2-turn routes. At the shortest distance, the difference between floors was not significant for 0 or 2 turns. At the middle distance, the first floor EED mean (M = 1.58) was greater than the second floor EED mean (M = 0.50) for 0-turn routes. For 2-turn routes, the first floor EED mean was not significantly different from the second floor EED mean. At the longest distance, the first floor EED mean (M = 1.42) (M = 1.71) was greater than the second floor EED mean (M = 0.53) (M = 0.32) for both 0-turn and 2-turn routes.

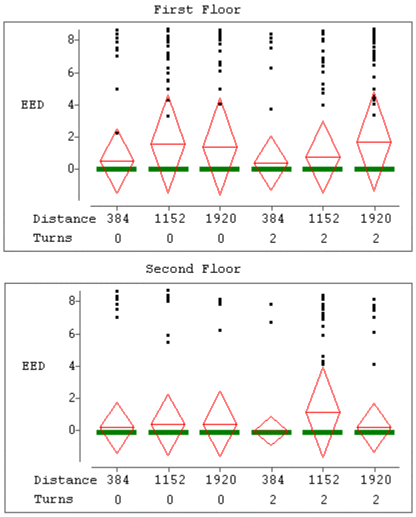


Figure 20. EED as a function of Distance, Turns, and Floor for trials 1- 5

Analysis of Learning Data by Trial

Because Trial was significant in the first MANOVA, a second analysis was done to assess the effect of Distance, Turns, Floor, and Order on POD and EED for each trial. The Out data were divided into 5 separate data sets. Each data set contained the data from a single trial block. An identical analysis to the analysis described in the previous section was run with the data from each trial. The only difference between the previous analyses and the analyses run on the individual trial block data were that Trial was no longer an independent variable in the analysis.

Analysis of Trial 1 Data. The table below contains the results of the multivariate tests for trial 1. Only the main effect of Turns and the Distance x Floor interaction were significant.

Table 31 MANOVA Test Criterion and F Approximations for Trial 1

Effect	Wilks' Lambda	F	Num df	Den df	p
Distance	0.830088	2.2932	4	94	0.0651
Turns	0.132669	75.1817	2	23	0.0001
Floor	0.816123	2.591	2	23	0.0966
Distance x Turns	0.866813	1.6668	4	90	0.1646
Distance x Floor	0.729016	4.0232	4	94	0.0047
Turns x Floor	0.811412	2.6728	2	23	0.0904
Distance x Turns x Floor	0.839268	2.1518	4	94	0.0805
Order	0.690251	0.9367	10	46	0.5094
Order x Distance	0.77568	0.6365	20	94	0.8753
Order x Turns	0.818822	0.4835	10	46	0.8921
Order x Floor	0.501446	1.896	10	46	0.0703
Order x Distance x Turns	0.79617	0.5432	20	90	0.9394
Order x Distance x Floor	0.621787	1.2604	20	94	0.2258
Order x Turns x Floor	0.539042	1.6654	10	46	0.1184

The table below contains the ANOVA results for the effects for which the multivariate test was significant. For both of these effects, only the univariate test for POD was significant.

Table 32 ANOVA Results for Effects Which Were Significant Using the Multivariate Criterion

Effect	Dependent Measure	F	Num df	Den df	Pr > F
Turns	POD	144.81	1	24	0.0001
	EED	2.51	1	24	0.1264
Distance x Floor	POD	8.50	2	48	0.0007
	EED	1.37	2	48	0.2640

Figure 21 shows the main effect of Turns for trial 1. The univariate ANOVA, following the MANOVA, shows that the mean POD for routes with 2 turns (M = 10.37) was significantly larger than the mean POD for routes with 0 turns (M = 0.53).

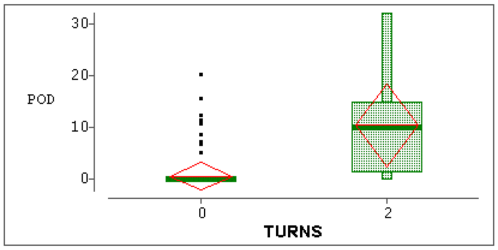


Figure 21. POD as a function of Turns for trial 1

Further analyses were run to identify significant differences among the means for the Distance x Floor interaction. In all analyses, unless explicitly described otherwise, Tukey's

HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at $p < .05$.

Two types of comparisons were made among the POD means. In the first comparison, means for the three distances were compared within each floor. On the first floor, the only significant difference was between the shortest (M = 2.78) and longest route (M = 6.03). On the second floor, both the means for the shortest (M = 2.82) and longest route (M = 4.31) were significantly less than the mean for the medium distance route (M = 8.18). The difference between the shortest and longest route was not significant.

In the second comparison, means for the two floors were compared within each distance. The difference between first floor and second floor routes was not significant at the shortest or longest distance. At the medium distance, the mean for second floor routes (M = 8.18) was significantly greater than the mean for first floor routes (M = 4.81).

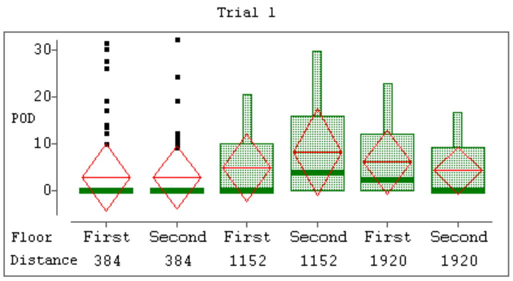


Figure 22. POD as a function of Distance and Floor for trial 1

Analysis of Trial 2 Data. The table below contains the results of the multivariate tests for trial 2. Only the main effect of Turns was significant.

Table 33 <u>MANOVA Test Criterion and F Approximations for Trial 2</u>

Effect	Wilks' Lambda	F	Num df	Den df	p
Distance	0.81590605	1.9608	4	94	0.1069
Turns	0.19764462	46.6852	2	23	0.0001
Floor	0.84926261	2.0412	2	23	0.1528
Distance x Turns	0.85252391	1.9516	4	94	0.1083
Distance x Floor	0.95177082	0.5881	4	94	0.6721
Turns x Floor	0.83775219	2.2272	2	23	0.1306
Distance x Turns x Floor	0.95899860	0.5923	4	1121	0.6689
Order	0.80949445	0.5127	10	46	0.8723
Order x Distance	0.67939887	1.0021	20	94	0.4675
Order x Turns	0.82500361	0.4644	10	46	0.9042
Order x Floor	0.66719144	1.0316	10	46	0.4329
Order x Distance x Turns	0.68673250	0.9716	20	94	0.5026
Order x Distance x Floor	0.71681133	0.8513	20	94	0.6465
Order x Turns x Floor	0.70871809	0.8641	10	46	0.5720

Table 32 contains the ANOVA results for the main effect of Turns. As was found in trial 1, only the univariate test for POD was significant.

Table 34 <u>ANOVA Results for Effects Which Were Significant Using the Multivariate Criterion</u>

Effect	Dependent Measure	F	Num df	Den df	Pr > F
Turns	POD	86.99	1	24	0.0001
	EED	1.82	1	24	0.1903

Figure 23 shows the POD distribution and means for 0-turn and 2-turn routes. As indicated by the univariate F-test following the MANOVA, POD was significantly greater for routes with 2 turns (<u>M</u> = 5.30) than for routes with 0 turns (<u>M</u> = 0.20).

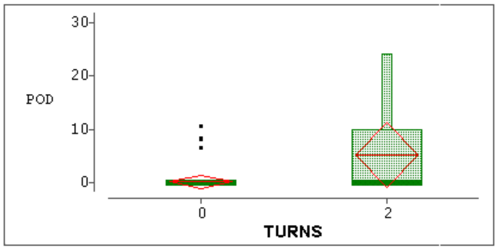


Figure 23. POD as a function of route turns for trial 2

Analysis of Trial 3 Data. The table below contains the results of the multivariate tests for trial 3. The main effects of Distance, Turns, and Floor were significant. The interaction of Turns x Floor and Distance x Turns x Floor were significant. There were also significant effects involving the order rooms within the trial. The Order x Distance x Turns and Order x Turns x Floor interactions were significant.

Table 35 MANOVA Test Criterion and F Approximations for Trial 3

Effect	Wilks' Lambda	F	Num df	Den df	p
Distance	0.56731617	7.7000	4	94	0.0001
Turns	0.46288102	13.3444	2	23	0.0001
Floor	0.36639980	19.8865	2	23	0.0001
Distance x Turns	0.91093027	1.221	4	90	0.3508
Distance x Floor	0.86029192	1.8364	4	94	0.1283
Turns x Floor	0.58948931	8.0084	2	23	0.0023
Distance x Turns x Floor	0.74370823	3.0319	4	76	0.0224
Order	0.80881345	0.5149	10	46	0.8708
Order x Distance	0.56982302	1.5263	20	94	0.0905
Order x Turns	0.71496944	0.8402	10	46	0.5932
Order x Floor	0.70531073	0.8773	10	46	0.5604
Order x Distance x Turns	0.47694297	2.1056	20	94	0.0089
Order x Distance x Floor	0.81564449	0.5041	20	94	0.9588
Order x Turns x Floor	0.47922891	2.0449	10	46	0.0499

The table below contains the ANOVA results for the effects for which the multivariate test was significant. For the Turns and Turns x Floor effects, the univariate test of POD was significant. The test of EED was significant for the Floor effect. Both the test of POD and EED were significant for the Distance effect. Neither of the univariate tests were significant for the Distance x Turns x Floor effect.

Both the test for POD and EED were significant for Order x Distance x Turns. Only the EED test was significant for Order x Turns x Elevation.

Table 36 ANOVA Results for Effects Which Were Significant Using the Multivariate Criterion

Effect	Dependent Measure	F	Num df	Den df	Pr > F
Distance	POD	9.46	2	48	0.0003
	EED	13.74	2	48	0.0001
Turns	POD	10.68	1	24	0.0033
	EED	0.20	1	24	0.6589
Floor	POD	1.12	1	24	0.2998
	EED	28.78	1	24	0.0001
Turns x Floor	POD	14.62	1	24	0.0008
	EED	2.84	1	24	0.1047
Distance x Turns x Floor	POD	1.51	2	39	0.2338
	EED	2.32	2	39	0.1130
Order x Distance x Turns	POD	3.14	10	48	0.0037
	EED	3.65	10	48	0.0011
Order x Turns x Elevation	POD	2.25	5	24	0.0815
	EED	3.07	5	24	0.0279

Further analyses were run to identify significant differences among the means for the Distance main effect and the interactions. In all analyses, unless explicitly described otherwise, Tukey’s HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at $p < .05$.

Figure 24 shows the POD distributions and means for the three route distances. The difference between the POD mean for the shortest distance ($M = 3.11$) and the other two distances ($M = 7.30$) ($M = 6.50$) was significant. The difference between the medium and long distance was not significant.

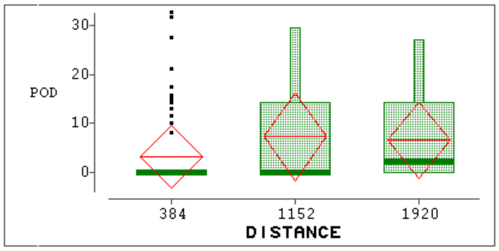


Figure 24. POD as a function of Distance for trial 3

Figure 25 shows the EED distributions and means for the three route distances. The effect followed the same pattern as found for the POD means. The mean for the shortest distance ($M = 0.95$) was significantly less than the means for the other two distances ($M = 2.39$) ($M = 2.65$). The difference between the medium and long distance was not significant.

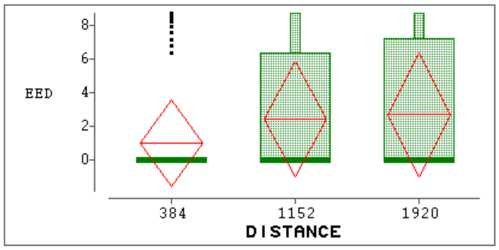


Figure 25. EED as a function of Distance for trial 3

Figure 26 shows the POD distributions and means for routes with 0 and 2 turns. The significant F-test, from the univariate test following the MANOVA, shows that the mean POD for routes with 0 turns (M = 3.62) is significantly less than the mean for routes with 2 turns (M = 7.65).

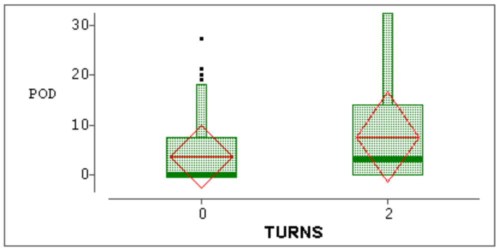


Figure 26. POD as a function of Turns for trial 3

Figure 27 shows the EED distributions and means for routes on the first and second floors. The significant F-test, from the univariate test following the MANOVA, shows that the mean EED for routes on the first floor (M = 2.42) is significantly greater than the mean for routes on the second floor (M = 1.33).

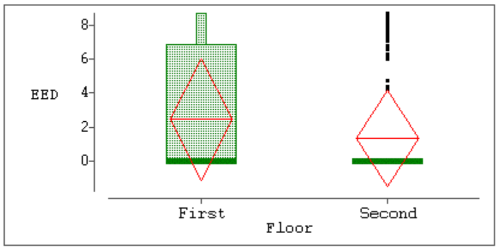


Figure 27. EED as a function of Floor for trial 3

Figure 28 shows the POD distributions and means for the Turns x Floor interaction. Two sets of comparisons were made. The first comparison was between 0-turn and 2-turn routes on each floor. On the first floor, the difference between the 0-turn and 2-turn route means was not significant. In contrast, on the second floor, this difference was significant. The mean for routes with 2 turns (M = 9.05) was larger than the mean for routes with 0 turns (M =2.09). The second comparison was between first and second floor routes for 0 and 2 turns. For routes with 0 turns, the first floor mean (M = 5.12) was significantly greater than the second floor mean. For routes with 2 turns, the first floor mean (M = 6.31) was significantly less than the second floor mean.

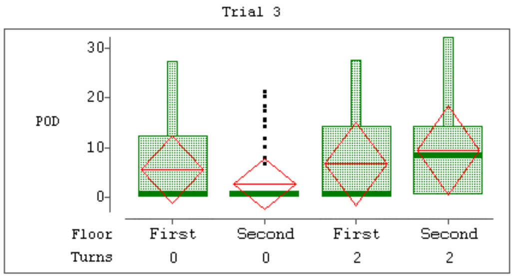
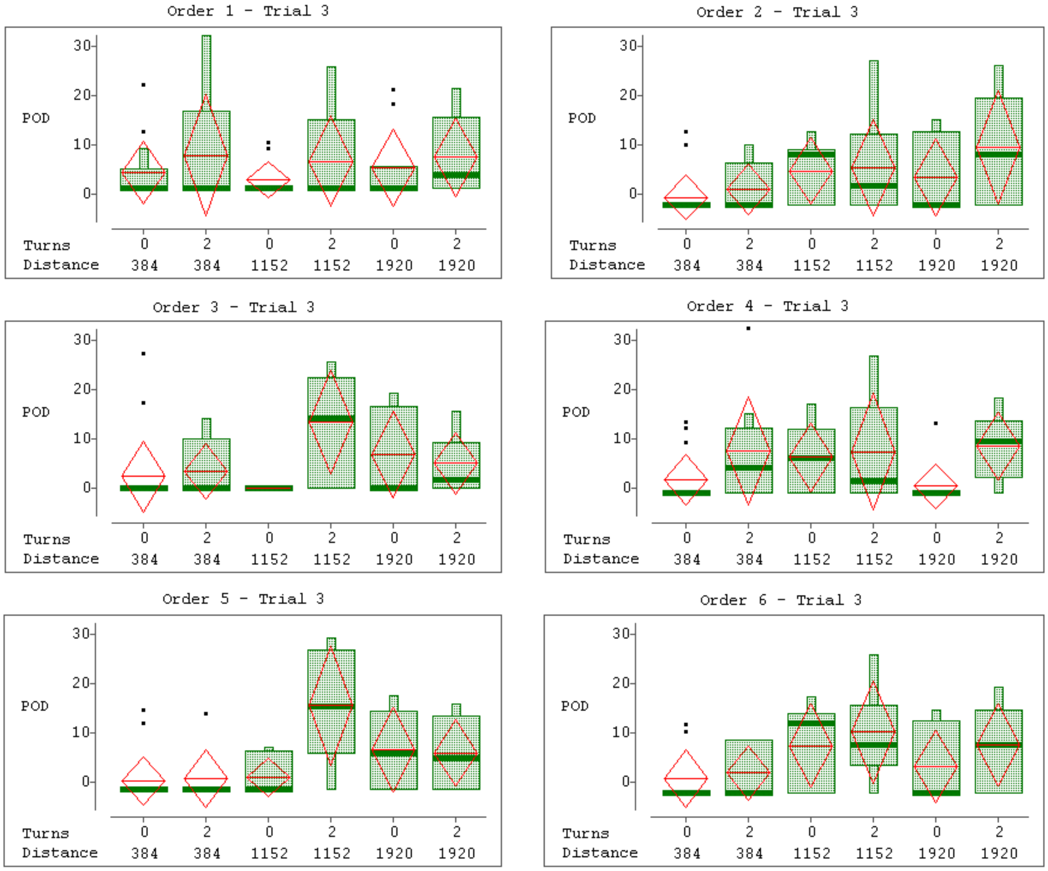


Figure 28. POD as a function of Floor and Turns for trial 3

Figure 29 shows the POD distributions and means for the Order x Distance x Turns interaction. Within each order, comparisons were made between the 0-turn and 2-turn routes at each distance. At the medium distance, for Orders 3 (M = 0) (M = 13.45) and 5 (M =2.30) (M =16.21), and at the longest distance, for Order 4 (M = 1.39) (M = 9.31), the mean for 0-turn routes was significantly less than the mean for 2-turn routes. No other comparisons were significant.


Order 1 - Trial 3

Order 2 - Trial 3

Order 3 - Trial 3

Order 4 - Trial 3

Order 5 - Trial 3

Order 6 - Trial 3

Figure 29. POD as a function of Order, Distance, and Turns for trial 3

Figure 30 shows the EED distributions and means for the Order x Distance x Turns interaction. Within each order, comparisons were made between the 0-turn and 2-turn routes at each distance. At the shortest distance, for Order 6 (M = 1.74) (M = 0.00), and at the medium distance, for Order 2 (M = 3.43) (M =1.27), the mean for 0-turn routes was significantly greater than the mean for 2-turn routes. For Order 5, at the medium distance, the mean for 0-turn routes (M = 1.23) was significantly less than the mean for 2-turn routes (M = 4.81). No other comparisons were significant.

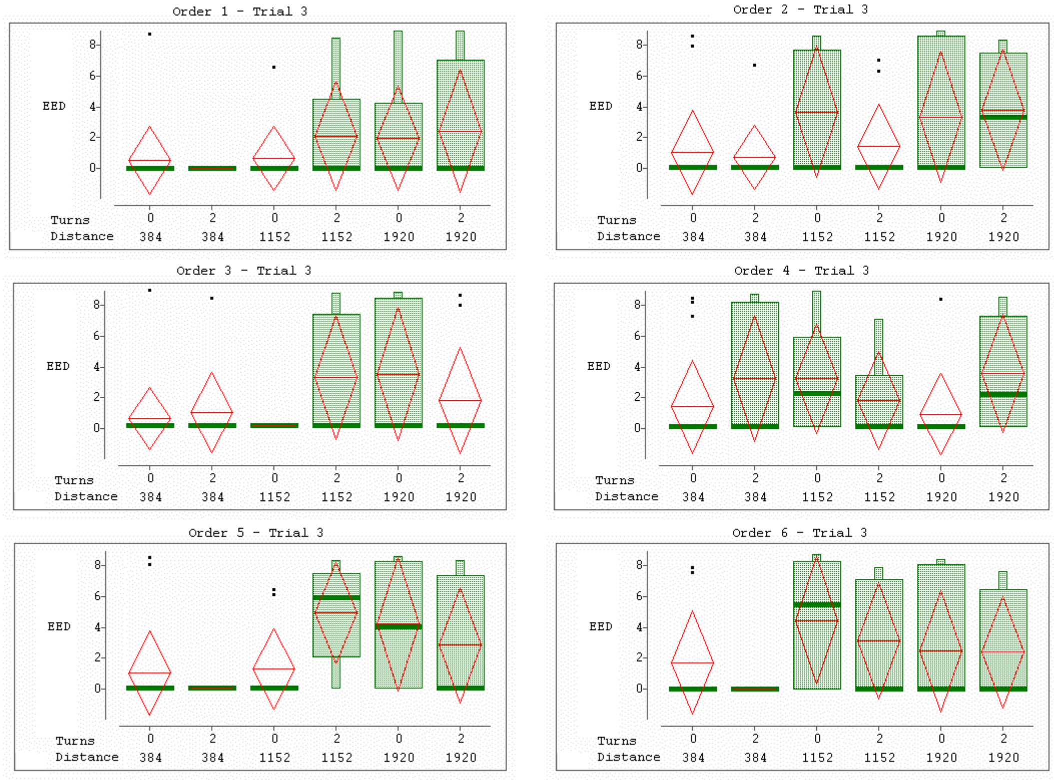


Figure 30. EED as a function of Order, Distance, and Turns for trial 3

Figure 31 shows the EED distributions and means for the Order x Turns x Floor interaction. Within each order, comparisons were made between the first and second floor routes for 0 and 2 turns. For 0-turn routes, in Orders 2 (M =3.88) (M = 0.78), 4 (M =2.49) (M =0.37), and 6 (M = 4.42) (M = 0.87), the mean for first floor routes was significantly greater than the mean for second floor routes. No other comparisons were significant.

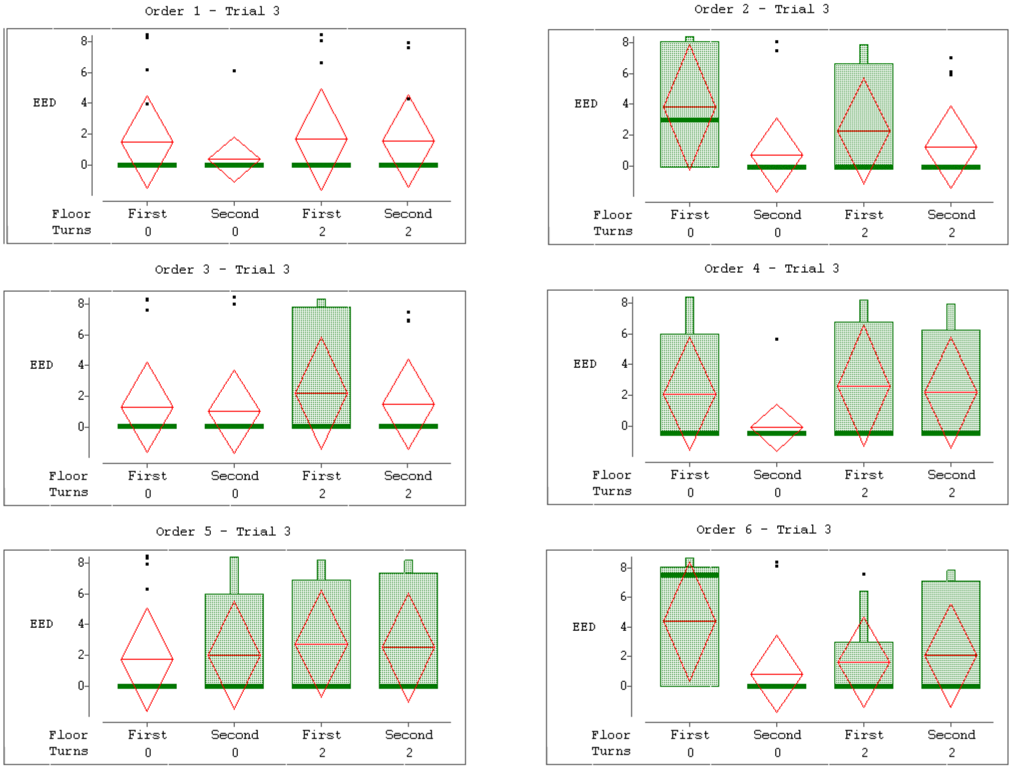


Figure 31. EED as a function of Order, Turns, and Floor for trial 3

Analysis of Trial 4 Data. The table below contains the results of the multivariate tests for trial 4. The main effects of Distance, Turns, and Floor were significant. The Turns x Floor interaction was the only significant interaction.

Table 37 MANOVA Test Criterion and F Approximations for Trial 4

Effect	Wilks' Lambda	F	Num df	Den df	p
Distance	0.67139799	5.1799	4	94	0.0008
Turns	0.54457229	9.6175	2	23	0.0009
Floor	0.48087119	12.4149	2	23	0.0002
Distance x Turns	0.92606919	0.9005	4	92	0.4671
Distance x Floor	0.82709330	2.2901	4	92	0.0656
Turns x Floor	0.56096804	9.0003	2	23	0.0013
Distance x Turns x Floor	0.85205927	2.1669	4	104	0.0778
Order	0.74578905	0.7266	10	46	0.6955
Order x Distance	0.81358573	0.5107	20	94	0.9559
Order x Turns	0.86027150	0.3595	10	46	0.9577
Order x Floor	0.59234474	1.3768	10	46	0.2210
Order x Distance x Turns	0.86949653	0.3331	20	92	0.9965
Order x Distance x Floor	0.77365976	0.6298	20	92	0.8805
Order x Turns x Floor	0.83978888	0.4196	10	46	0.9299

The table below contains the ANOVA results for the effects for which the multivariate test was significant. Both the test for POD and EED were significant for the main effect of Distance. Neither univariate tests were significant for the main effect of Turns. Only the EED test was significant for the main effect of Floor. For the Turns x Floor interaction, only the POD test was significant.

Table 38 ANOVA Results for Effects Which Were Significant Using the Multivariate Criterion

Effect	Dependent Measure	F	Num df	Den df	Pr > F
Distance	POD	6.67	2	48	0.0028
	EED	7.91	2	48	0.0011
Turns	POD	3.49	1	24	0.0740
	EED	2.35	1	24	0.1381
Floor	POD	1.74	1	24	0.2002
	EED	21.07	1	24	0.0001
Turns x Floor	POD	7.88	1	24	0.0098
	EED	0.26	1	24	0.6171

Further analyses were run to identify significant differences among the means for the Distance main effect and the interactions. In all analyses, unless explicitly described otherwise, Tukey's HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at p < .05.

Figure 32 shows the POD distributions and means for the three route distances. The middle distance mean (M = 4.95) was significantly greater than the shortest distance mean (M = 2.07).

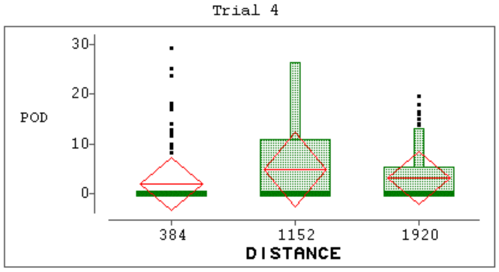


Figure 32. POD as a function of Distance for trial 4

Figure 33 shows the EED distributions and means for the three route distances. Both the middle (M = 1.83) and long distance (M = 1.46) means were significantly greater than the short distance mean (M = 0.45).

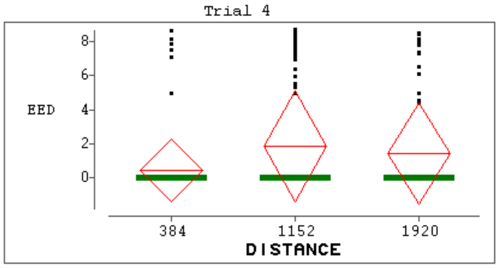


Figure 33. EED as a function of Distance for trial 4

Figure 34 shows the EED distributions and means for first and second floor routes. The univariate F-test, following the MANOVA, shows that the mean EED for first floor routes (M = 1.60) was significantly greater than the mean EED for second floor routes (M =0.71).

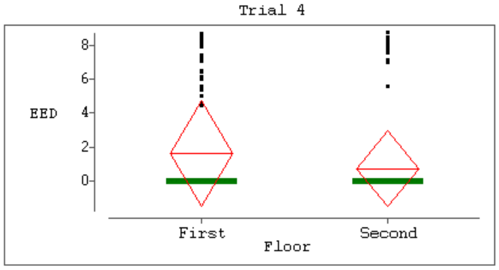


Figure 34. EED as a function of Floor for trial 4

Figure 35 shows the POD distributions and means for the Turns x Floor interaction. Two sets of comparisons were made between the means. In the first comparison, means for the 0-turn and 2-turn routes were compared within each floor. On the first floor, the difference between 0-turn and 2-turn routes was not significant. On the second floor, the mean for 0-turn routes (M = 1.72) was significantly less than the mean for 2-turn routes (M =

4.55). In the second comparison, means for each floor were compared within 0-turn and 2-turn routes. For 0-turn routes, the mean for first floor routes (M = 3.72) was significantly greater than the mean for second floor routes (M = 1.72). For 2-turn routes, the difference between floors was not significant.

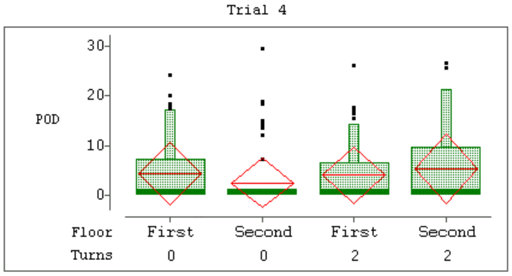


Figure 35. POD as a function of Floor and Turns for trial 4

Analysis of Trial 5 Data. The table below contains the results of the multivariate tests for trial 5. The main effects of Distance, Turns, and Floor were significant. The Turns x Floor, and Distance x Turns x Floor were also significant.

Table 39 MANOVA Test Criterion and F Approximations for Trial 5

Effect	Wilks' Lambda	F	Num df	Den df	p
Distance	0.73575709	3.8969	4	94	0.0057
Turns	0.74336400	3.9702	2	23	0.0330
Floor	0.52623111	10.3535	2	23	0.0006
Distance x Turns	0.86132389	1.8212	4	94	0.1312
Distance x Floor	0.85622526	1.8965	4	94	0.1175
Turns x Floor	0.69228399	5.1117	2	23	0.0146
Distance x Turns x Floor	0.80478714	3.0970	4	108	0.0186
Order	0.80889949	0.5146	10	46	0.8710
Order x Distance	0.61682244	1.2844	20	94	0.2092
Order x Turns	0.80392260	0.5304	10	46	0.8596
Order x Floor	0.67086671	1.0162	10	46	0.4449
Order x Distance x Turns	0.72197011	0.8314	20	94	0.6704
Order x Distance x Floor	0.76980811	0.6568	20	94	0.8578
Order x Turns x Floor	0.68607052	0.9536	10	46	0.4953

The table below contains the ANOVA results for the effects for which the multivariate test was significant. Neither of the univariate tests for Distance, Turns, or Distance x Turns interaction were significant. For the Floor main effect, only the EED test was significant. Both the POD and EED tests were significant for the Distance x Turns x Floor interaction.

Table 40 ANOVA Results for Effects Which Were Significant Using the Multivariate Criterion

Effect	Dependent Measure	F	Num df	Den df	Pr > F
Distance	POD	1.37	2	48	0.2645
	EED	2.06	2	48	0.1380
Turns	POD	0.27	1	24	0.6079
	EED	1.38	1	24	0.2521
Floor	POD	0.75	1	24	0.3936
	EED	8.13	1	24	0.0088
Turns x Floor	POD	3.51	1	24	0.0734
	EED	0.15	1	24	0.6980
Distance x Turns x Floor	POD	6.20	2	55	0.0037
	EED	4.99	2	55	0.0102

Figure 36 shows the EED distributions and means for first and second floor routes. The univariate F-test, following the MANOVA, shows that the mean EED for first floor routes (M = 0.87) was significantly greater than the mean EED for second floor routes (M = 0.35).

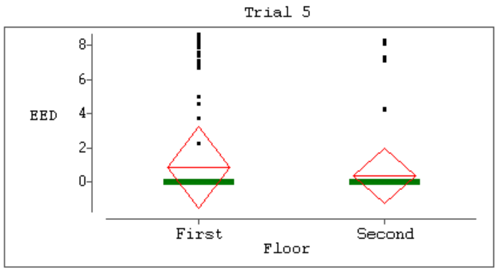


Figure 36. EED as a function of Floor for trial 5

Further analyses were run to identify significant differences among the means from the Distance x Turns x Floor interaction. In all analyses, unless explicitly described otherwise, Tukey’s HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at $p < .05$.

Figures 37 and 38 show the POD and EED distributions and means for the Distance x Turns x Floor interaction. Three sets of comparisons were made for the POD and EED means. In the first, means for each distance were compared within 0-turn and 2-turn routes within each floor. On the first floor, there were no significant differences among the distance means for 0-turn routes. For 2-turn routes, the short (M = 0.38) and middle distance (M = 0.28) EED means were significantly less than the long distance EED mean (M = 1.49).

On the second floor, there were no significant differences among the distance means for 0-turn routes. For 2-turn routes, the middle distance POD mean (M = 4.26) was significantly greater than the long distance POD mean (M = 0.47).

In the second set of comparisons, means for 0-turn and 2-turn routes were compared within each distance and within each floor. There was no difference between 0-turn and 2-turn route POD means on the first floor at any distance. For the middle distance on the first floor, the 0-turn route EED mean (M = 1.73) was significantly greater than the 2-turn route EED mean (M = 0.28).

On the second floor, there were several significant differences between 0-turn and 2-turn routes. For the short distance, the 0-turn route EED mean (M = 0.57) was significantly greater than the 2-turn route EED mean (M = 0.00). For the middle distance, the 0-turn route POD mean (M = 0.47) was significantly less than the 2-turn route POD mean (M = 4.26).

In the third set of comparisons, means for the first and second floor routes were compared within each distance and within 0-turn and 2-turn routes. For middle distance routes with 0 turns, the POD (M = 2.80) and EED (M = 1.73) means for the first floor were significantly greater than the POD (M = 0.47) and EED mean (M = 0.27) for the second floor. For routes with 2 turns, the first floor POD mean (M = 0.75) was significantly less than the second floor POD mean (M = 4.26).

At the long distance, for routes with 2-turns, the first floor EED mean (M = 1.49) was significantly greater than the second floor EED mean (M = 0.00).

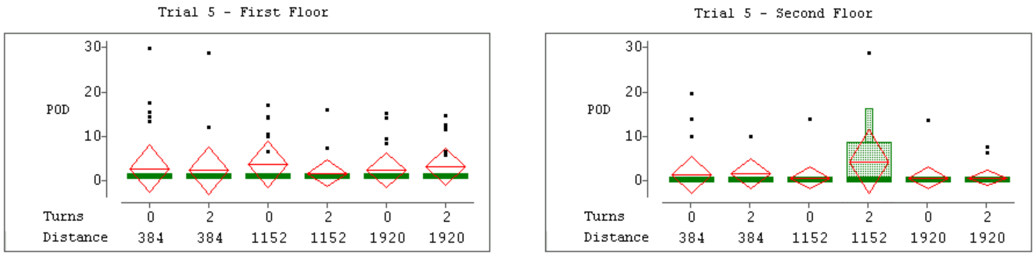


Figure 37. POD as a function of Distance, Turns, and Floor for trial 5

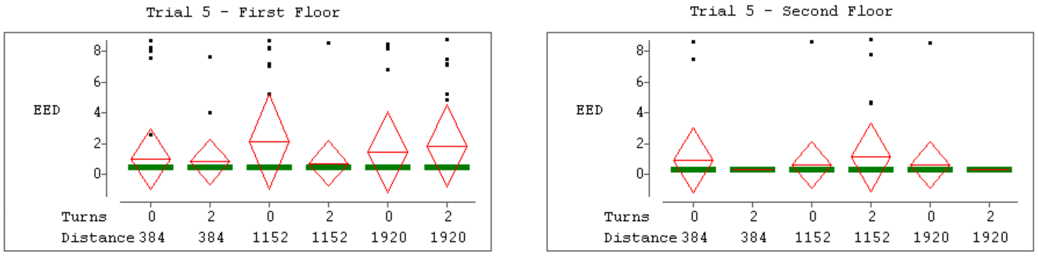


Figure 38. EED as a function of Distance, Turns, and Floor for trial 5

Summary of Out Data Analysis. The table below summarizes the results of the analysis of the Out data. The pattern of results found in the analysis of all the Out data were repeated in the analysis of individual trial data. The Distance main effect, when significant at the univariate level, was significant for both POD and EED. In contrast, the Turns main effect was significant only for POD while the Floor main effect was significant only for EED. The Distance x Turn interaction was significant in the overall analysis but not in the analysis of individual trial data. The Distance x Floor interaction was significant in the overall analysis and in the analysis of trial 1 data. The Turns x Floor interaction was significant in the overall analysis and the analysis of trial 3, trial 4, and trial 5 data. The Distance x Turns x Floor interaction was significant in the overall analysis and the analysis of trials 3, 4, and 5 data.

Table 41 Summary of Significant Effects in Analysis of Out Data in Learning Trials 1 - 5

	Trial and Dependent Variable																	
	O			1			2			3			4			5		
Effect	M	P	E	M	P	E	M	P	E	M	P	E	M	P	E	M	P	E
Tr	✓	✓	✓															
D	✓	✓	✓							✓	✓	✓	✓	✓	✓	✓		
T	✓	✓		✓	✓		✓	✓		✓	✓		✓			✓		
F	✓		✓							✓		✓	✓		✓	✓		✓
D x T	✓	✓																
D x F	✓	✓	✓	✓	✓													
T x F	✓	✓								✓	✓		✓	✓		✓		
DxTxF	✓	✓	✓							✓				✓		✓	✓	✓

Note: A ✓ indicates a significant effect at α = .05. In the Effect column Tr = Trial, D = Distance, T = Turns, F = Floor. In the Trial and Dependent Variable row O = Overall (trials 1 - 5), 1 = Trial 1, 2 = Trial 2, 3 = Trial 3, 4 = Trial 4, 5 = Trial 5, M = MANOVA, P = POD ANOVA, E = EED ANOVA

ANOVA Analysis of the Back Data for Trials 1 - 5

SAS PROC GLM was used to analyze the Back data using an ANOVA with Trial, Distance, Turns, Floor, and Order as independent variables. The main effects, 2-way, and 3-way interactions were tested for Distance, Turns, Floor, and Order. Only the main effect of Trial was tested in this analysis. Since the main effect of Trial was not significant, there was no analysis of the Back data within each trial block.

The table below summarizes the results of the ANOVA. The Distance, Turns, and Distance x Turns effects were significant.

Table 42 Results of Back Data ANOVA for Trials 1 - 5

Source	DF	SS	MS	F	Pr > F
Trial	4	0.568984	0.142246	1.02	0.4009
Distance	2	4.891779	2.445889	3.39	0.0418
Turns	1	8.189144	8.189144	4.85	0.0375
Floor	1	0.172246	0.172246	0.47	0.4998
Distance*Turns	2	4.891779	2.445889	3.39	0.0418
Distance*Floor	2	0.338732	0.169366	0.7	0.5011
Turns*Floor	1	0.172246	0.172246	0.47	0.4998
Distance*Turns*Floor	2	0.338732	0.169366	0.73	0.4878
Order	5	5.521198	1.10424	0.65	0.6612
Order*Distance	10	4.574479	0.457448	0.63	0.7768
Order*Turns	5	5.521198	1.10424	0.65	0.6612
Order*Floor	5	1.728668	0.345734	0.94	0.4719
Order*Distance*Turns	10	4.574479	0.457448	0.63	0.7768
Order*Distance*Floor	10	1.929896	0.19299	0.8	0.6303
Order*Turns*Floor	5	1.728668	0.345734	0.94	0.4719

The main effect of Turns indicates that POD for 2-turn routes (M = 0.32) was significantly greater than POD for 0-turn routes (M = 0.00), as shown in Figure 39.

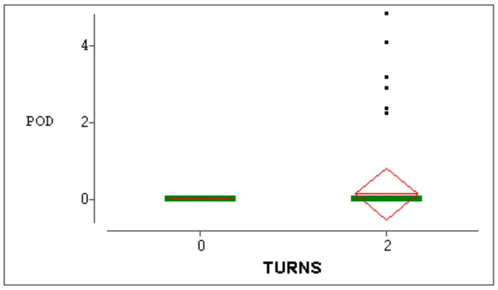


Figure 39. POD as a function of Turns

Further analyses were run to identify significant differences among the means for the Distance main effect and the Distance x Turn interaction. In all analyses, unless explicitly described otherwise, Tukey's HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at p < .05.

The POD distribution and means for the three route distances are shown in Figure 40. POD for the middle distance (M = 0.12) was significantly greater than POD for the shortest distance (M = 0.00).

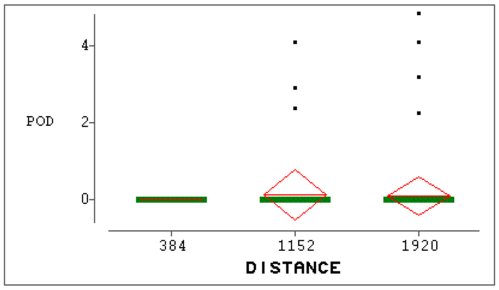


Figure 40. POD as a function of Distance

Figure 41 shows the distribution and means for the Distance x Turns interaction. Two sets of comparisons were made. In the first set, means for 0-turn and 2-turn routes were compared within each distance. At the shortest and middle distance, the difference between 0-turn and 2-turn routes was not significant. At the longest distance, POD for 2-turn routes (M = 0.15) was greater than POD for 0-turn routes (M = 0.00). In the second set of comparisons, means for the distances were compared within 0-turn and 2-turns. For 2-turn routes, POD for the middle distance (M = 0.24) was significantly greater than POD for the shortest distance (M = 0.00). No other comparisons were significant.

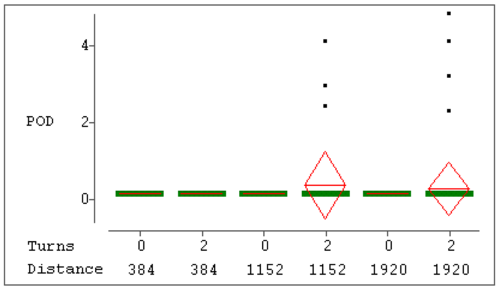


Figure 41. POD as a function of Distance and Turns

Post Learning Trials Measurements

Measures of Knowledge of the VE

After participants completed the six blocks of learning trials, they performed four tasks which measured their knowledge of room location in the virtual environment. The four tasks were (a) a route distance estimation task, (b) a pointing task, (c) a room location decision task, and (d) a navigation task.

In the route distance estimation task, participants estimated the distance between two rooms or between the starting point and a room. The distance estimate was transformed into Distance Estimate Accuracy (DEA) which is an error percentage. Positive DEA indicates the participant overestimated the distance. Negative DEA indicates the participant underestimated the distance.

In the pointing task, participants were placed at the starting point or at a room and asked to point at the door of another room (which they could not see). Both the azimuth and elevation of their response were collected. The azimuth measure was transformed into a difference score, Azimuth Accuracy (AA), so that a positive AA score indicates the estimated azimuth is farther from the start position (0^o) than the target azimuth. The elevation measure was transformed into a difference score, Elevation Accuracy (EA), so that a positive EA indicates the participant pointed above the target and a negative EA indicates the participant pointed below the target.

In the room location decision task, participants were presented with a prime and then a target room. They had to decide if the target room was on the same floor as the prime. The reaction time (RT) for each response was collected.

In the navigation task, participants navigated from one room to another. POD and EED, the same measures used in the learning trials, were collected during the navigation task.

Types of Routes

In the distance estimation and the pointing tasks, participants were presented with either room-room or starting point-room pairs. The room-room pairs required them to provide estimates, of distance or direction, along routes that were not part of the learning trials. Responses to the room-room pairs (novel routes) required participants to access survey knowledge of the virtual environment. In contrast, the starting-point room pairs required them to provide estimates, of distance or direction, along the routes used in the learning trials. Responses to the starting point-room trials required participants to access route knowledge of the virtual environment. Because the responses to the room-room pairs were intended to access a different type of knowledge than the responses to the starting point-room pairs, the data for the two types of origin-target pairs were separated prior to the analyses.

The target rooms in the in the novel routes were defined by the combination of Distance (2 levels), Turns (2 levels), Elevation (2 levels), and Group (2 levels). The target rooms in the starting point-room pairs (known routes) were defined by the combination of Distance (3 levels), Turns (2 levels), and Floor (2 levels).

Data Screening

Prior to analyzing the data, the data were screened for univariate and multivariate outliers using the same criterion established during the data screening of the learning trials data. The tables below show the number of outliers for each of the dependent measures. Fifty-six univariate or multivariate outlier observations were dropped from the 900 original observations.

Table 43 Outliers Using a Standardized Score of 3.29 as a Cutoff for Known Routes

	Dependent Measure		
	DEA	AA	EA
Number of univariate outliers	5	2	3
Total number of outliers	5	4	5

Table 44 Outliers Using a Standardized Score of 3.29 as a Cutoff for Novel Routes

	Dependent Measure					
	DEA	AA	EA	RT	POD	EED
Number of univariate outliers	5	0	9	10	3	7
Total number of outliers	7	0	10	10	11	15

After screening the data for outliers, the normality of the distribution of each variable was assessed. None of the distributions deviated enough from the normal distribution to warrant transformation prior to using the data in subsequent analyses.

Correlations between the dependent measures were calculated to help decide if the data should be analyzed using a MANOVA or separate ANOVAs. Tables 3 and 4 show the correlations between the dependent measures for known and novel routes.

As shown in the table below, there appears to be no relationship among the dependent measures for the data assessing knowledge of known routes. The low correlations suggest that separate ANOVAs should be used to analyze the data.

Table 45 Correlations Between Dependent Measures for Known Routes

	DEA	AA
DEA		
AA	-0.06	
EA	0.11	-0.01

For all but two of the dependent measures for data assessing knowledge of novel routes, the relationship is too weak to justify using a MANOVA. However, POD and EED are more strongly associated than the others. They will be analyzed using a MANOVA in the same manner that POD and EED were analyzed for the learning trials. All the remaining data will be analyzed using separate ANOVAs.

Table 46 Correlations Between Dependent Measures for Novel Routes

	DEA	RT	AA	EA	POD
DEA					
RT	0.07				
AA	0.08	-0.11			
EA	-0.02	-0.09	-0.03		
POD	0.03	0.12	0.01	-0.03	
EED	-0.07	0.19	-0.01	-0.06	0.35

Relationship Between Dependent Measures and Participant Characteristics

The participant questionnaire was designed to assess the participant's experience with computers and computer games. If any of these characteristics were moderately or strongly correlated with the dependent measures, they could have been treated as covariates in the analyses. As shown in the following tables, there was a non-existent to weak relationship between the responses to the participant questionnaire and the dependent measures. None of these characteristics was used as a covariate.

Table 47 Correlations Between Participant Characteristics and Post-Learning Dependent Measures

	Dependent Measure					
Characteristic	DEA	AA	EA	RT	POD	EED
Gender	-0.0181	-0.0718	0.0557	-0.1845	0.0286	0.0351
Age	0.0803	-0.0150	0.0384	-0.0336	-0.0476	-0.0650
Year in School	-0.1216	-0.0088	0.0593	-0.1795	-0.0717	-0.1005
Sense of Direction	-0.0630	-0.0633	-0.0215	-0.0433	-0.0436	-0.0709
Computer Use	0.0215	-0.0843	0.0234	0.0971	0.0466	0.0354
Joystick Use	-0.0023	0.0367	0.1121	-0.0948	-0.0571	-0.1765
Wingman Use	-0.0306	-0.0030	-0.0405	0.0802	-0.0142	-0.0366
Game Experience	-0.0836	0.0804	0.0933	-0.0539	-0.1597	-0.2048
FP Game Experience	-0.0806	-0.0438	0.0389	0.1314	-0.1166	-0.1219
Game Frequency	-0.0301	-0.0573	-0.1039	0.2461	0.0745	0.0913

Route Distance Estimation Task

Known Routes. The table below shows the results of the DEA ANOVA for known routes. Distance, Turns, and Floor are the factors describing the target room location in relation to the participant's location when making the distance estimate. Order is the order in which the room pairs were presented. The main effects of Turns and Floor, and the Distance x Turns, Distance x Floor, and Turns x Floor interactions were significant.

Table 48 ANOVA Results for DEA for Known Routes

Effect	df	MS	F	Pr > F
Distance	2	9130.51	2.80	0.0702
Turns	1	6460.53	5.38	0.0289
Floor	1	16425.11	20.16	0.0001
Distance x Turns	2	3502.81	3.27	0.0466
Distance x Floor	2	4661.15	8.36	0.0008
Turns x Floor	1	4686.34	4.78	0.0384
Distance x Turns x Floor	2	311.78	0.86	0.4304
Order	4	18566.11	1.29	0.3004
Order x Distance	8	2797.20	0.86	0.5569
Order x Turns	4	679.51	0.57	0.6898
Order x Floor	4	597.68	0.73	0.5776
Order x Distance x Turns	8	1590.92	1.48	0.1875
Order x Distance x Floor	8	668.22	1.20	0.3200
Order x Turns x Floor	4	1248.34	1.27	0.3071

DEA means for 0-turn routes (M = -6.15) was significantly greater than the mean for 2-turn routes (M = -12.22). Figure 42 shows the DEA distribution and means for the Turns main effect.

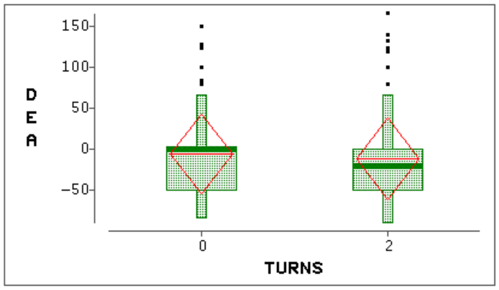


Figure 42. DEA as a function of Turns for known routes

DEA for routes leading to the second floor (M = -0.86) was more accurate than DEA for routes on the first floor (M = -16.25). Figure 43 shows the DEA distribution and means for the Floor main effect.

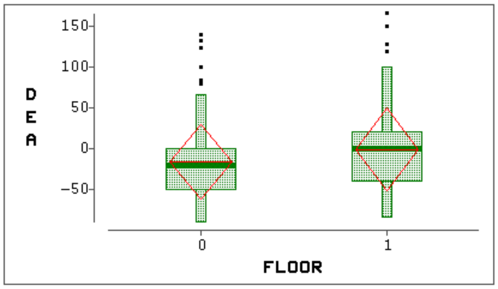


Figure 43. DEA as a function of Floor for known routes

Further analyses were run to identify significant differences among the means for the significant interactions. In all analyses, unless explicitly described otherwise, Tukey's HSD test was used to assess the significance of differences between means. Results of this analysis that are reported below are significant at $p < .05$.

Figure 44 shows the DEA distributions and means for the Distance x Turns interaction. Two sets of comparisons were made between the means. In the first comparison, means for the 0-turn and 2-turn routes were compared within each distance. At the longest distance, DEA for 0-turn routes (M = 7.48) was significantly greater than DEA for 2-turn routes (M = -13.25). In the second comparison, means for each distance were compared within 0-turn and 2-turn routes. For 0-turn routes, DEA for the longest distance was significantly greater (M = 7.48) than DEA for the shortest distance (M = -15.09). For 2-turn routes, there were no significant differences.

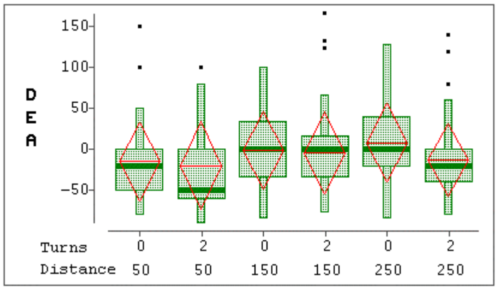


Figure 44. DEA as a function of Distance x Turns for known routes

Figure 45 shows the DEA distributions and means for the Distance x Floor interaction. Two sets of comparisons were made between the means. In the first comparison, means for the first floor and second floor routes were compared within each distance. At the shortest distance, DEA for routes leading to the second floor (M = -3.02) was more accurate than DEA for routes on the first floor (M = -29.68). At the longest distance, DEA for routes leading to the second floor (M = 1.05) was more accurate than DEA for routes on the first floor (M = -6.80). In the second comparison, means for each distance were compared within each floor. For first floor routes, DEA for the middle (M = -

5.82) and longest distance (M = -6.80) was significantly greater than DEA for the shortest distance (M = -29.68). For second floor routes, the differences were not significant.

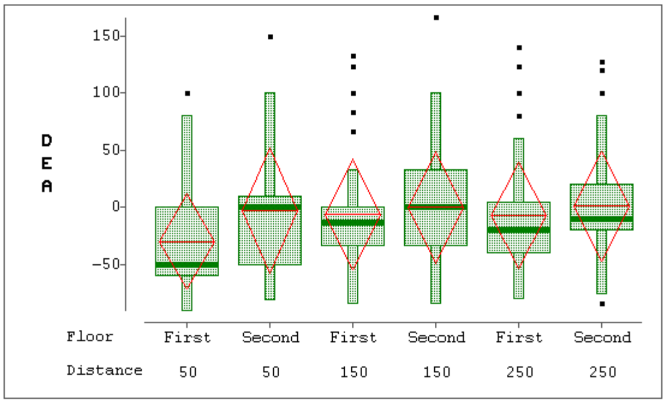


Figure 45. DEA as a function of Distance x Floor for known routes

Figure 46 shows the DEA distributions and means for the Turns x Floor interaction. Two sets of comparisons were made between the means. In the first comparison, means for the first floor and second floor routes were compared within 0-turn and 2-turn routes. For 0-turn routes, DEA for rooms on the second floor (M = 0.19) was significantly greater than DEA for rooms on the first floor (M = -12.32). For 2-turn routes, DEA for rooms on the second floor (M = -2.32) was significantly greater than DEA for rooms on the first floor (M = -21.45).

In the second comparison, means for 0-turn and 2-turn routes were compared within each floor. For routes on the first floor, DEA for 0-turn routes (M = -12.32) was significantly greater than DEA for 2-turn routes (M = -21.45). For second floor routes, the differences were not significant.

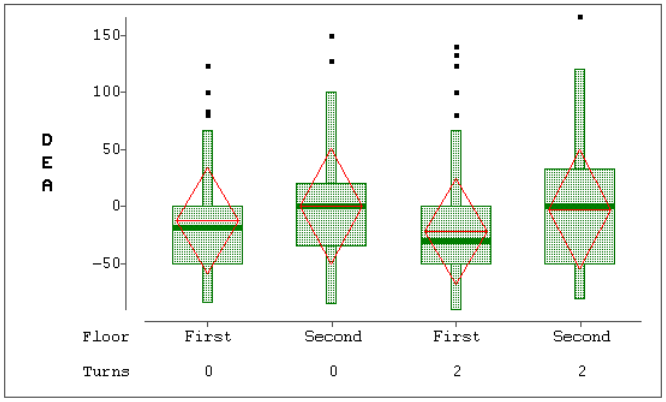


Figure 46. DEA as a function of Turns x Floor for known routes

Novel Routes. The table below shows the results of the DEA ANOVA for novel routes. Distance, Turns, and Elevation describe the target room location in relation to the participant’s location when making the distance estimate. Group is the target room's semantic group. Order is the order in which the room pairs were presented. The main effect Elevation, and the Order x Turns interaction were significant.

Table 49 ANOVA Results for Distance Estimation Data for Novel Routes

Effect	df	MS	F	Pr > F
Distance	1	545.09	0.27	0.6058
Turns	1	1584.37	0.71	0.4085
Elevation	1	19703.22	5.66	0.0253
Group	1	534.44	0.31	0.5821
Distance x Turns	1	156.92	0.13	0.7246
Distance x Elevation	1	79.63	0.09	0.7703
Distance x Group	1	47.47	0.03	0.8735
Turns x Elevation	1	5317.22	3.62	0.0692
Turns x Group	1	2666.02	2.57	0.1217
Elevation x Group	1	324.55	0.09	0.7611
Distance x Turns x Elevation	1	2853.03	1.88	0.1838
Distance x Turns x Group	1	1183.39	0.94	0.3461
Distance x Elevation x Group	1	143.72	0.19	0.6698
Turns x Elevation x Group	1	1669.56	1.62	0.2173
Order	4	7392.48	0.60	0.6656
Order x Distance	4	2467.75	1.24	0.3208
Order x Turns	4	8107.10	3.62	0.0186
Order x Elevation	4	1398.74	0.40	0.8055
Order x Group	4	2238.37	1.30	0.2963
Order x Distance x Turns	4	2084.53	1.69	0.1846
Order x Distance x Elevation	4	1328.97	1.45	0.2469
Order x Distance x Group	4	2196.11	1.20	0.3365
Order x Turns x Elevation	4	1202.63	0.82	0.5262
Order x Turns x Group	4	1000.29	0.96	0.4451
Order x Elevation x Group	4	2664.93	0.78	0.5512

DEA for routes leading to the another floor (M = -18.27) was significantly less than DEA for routes on the same floor (M = -0.28). Figure 6 shows the DEA distribution and means for the Elevation main effect.

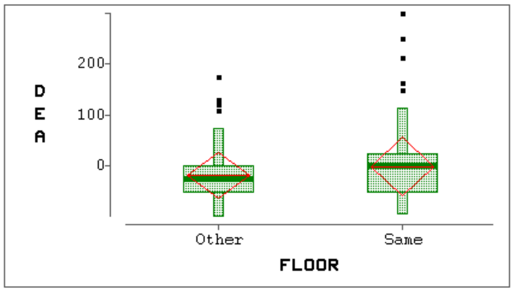


Figure 47. DEA as a function of Elevation for novel routes

In Order 2, DEA for 0-turn routes (M = -15.38) was significantly greater than for 2-turn routes (M = -33.24). Figure 48 shows the DEA distribution and means for the Order x Turns interaction.

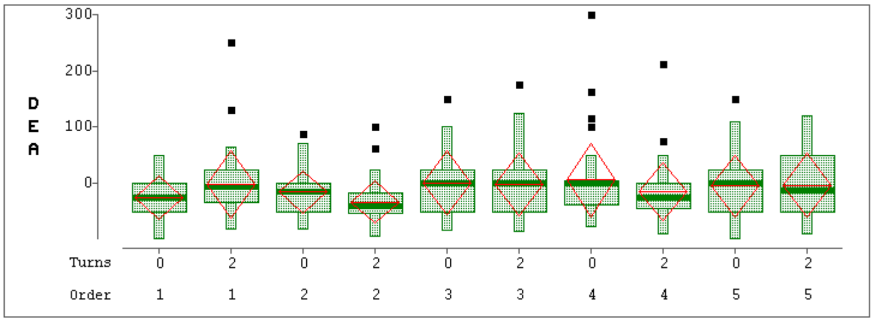


Figure 48. DEA as a function of Order x Turns for novel routes

Pointing Task - Azimuth Estimation

Known Routes. The table below shows the results of the AA ANOVA for known routes. Distance, Turns, and Floor are the factors describing the target room location in relation to the participant's location when making the distance estimate. Order is the order in which the room pairs were presented. The main effects of Distance and Floor, and the Distance x Turns interaction were significant.

Table 50 ANOVA Results for Pointing Task-Azimuth Accuracy for Known Routes

Effect	df	MS	F	Pr > F
Distance	2	1322.11	16.77	0.0001
Turns	1	313.15	3.88	0.0606
Floor	1	1249.65	21.73	0.0001
Distance x Turns	2	255.18	3.78	0.0301
Distance x Floor	2	22.19	0.53	0.5949
Turns x Floor	1	11.27	0.23	0.6373
Distance x Turns x Floor	2	176.26	2.86	0.0673
Order	5	220.54	1.65	0.1864
Order x Distance	10	52.74	0.67	0.7471
Order x Turns	5	150.74	1.87	0.1380
Order x Floor	5	110.09	1.91	0.1292
Order x Distance x Turns	10	60.53	0.90	0.5436
Order x Distance x Floor	10	36.22	0.86	0.5778
Order x Turns x Floor	5	20.23	0.41	0.8375

AA for the longest distance (M = 4.49) and the middle distance (M = 3.91) were significantly greater than AA for the shortest distance (M = -0.25). Figure 49 shows the AA distribution and means for the Distance main effect.

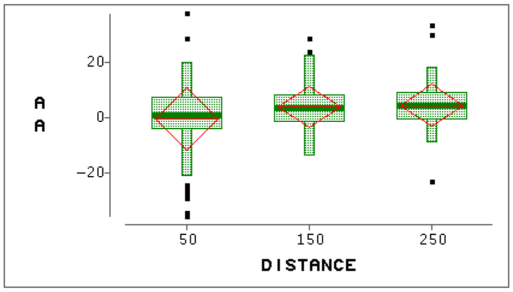


Figure 49. AA as a function of Distance for known routes

AA for rooms on the second floor (M = 0.07) was significantly less than AA for rooms on the first floor (M = 4.46). Figure 50 shows the AA distribution and means for the Floor main effect.

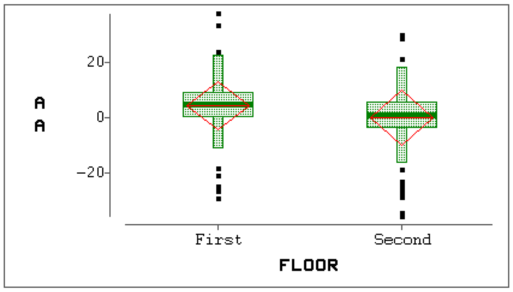


Figure 50. AA as a function of Floor for known routes

Figure 51 shows the AA distribution and means for the Distance x Turns interaction. Two sets of comparisons were made between the means. In the first comparison, means for the 0-turns and 2-turn routes were compared within each distance. For the middle distance, AA for rooms separated by 2 turns (M = 2.39) was significantly less than AA for room separated by 0 turns (M = 5.42). In the second set of comparisons, means for each distance were compared with 0-turn and 2-turn routes. None of the differences were significant.

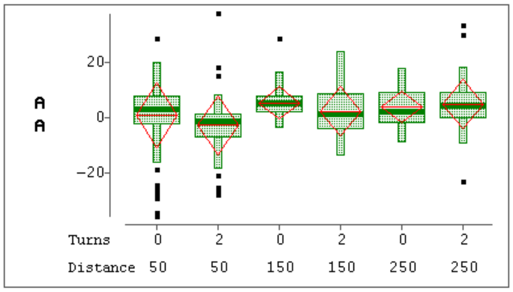


Figure 51. AA as a function of Distance x Turns for known routes

Novel Routes. The table below shows the results of the AA ANOVA for novel routes. Distance, Turns, and Elevation describe the target room location in relation to the participant's location when making the distance estimate. Group is the target room's semantic group. Order is the order in which the room pairs were presented. The main effect of Group, the Distance x Turns, Distance x Group, Turns x Group, Elevation x Group, Turns x Elevation x Group, and Order x Elevation x Group interactions were significant.

Table 51 ANOVA Results for Pointing Task-Azimuth Accuracy for Novel Routes

Effect	df	MS	F	Pr > F
Distance	1	250.98	0.04	0.8391
Turns	1	6645.58	1.04	0.3170
Elevation	1	2356.05	0.81	0.3779
Group	1	73949.56	13.61	0.0012
Distance x Turns	1	22603.91	6.22	0.0199
Distance x Elevation	1	5463.75	1.02	0.3223
Distance x Group	1	11224.07	5.41	0.0288
Turns x Elevation	1	24054.74	3.05	0.0940
Turns x Group	1	72202.74	12.66	0.0016
Elevation x Group	1	66911.15	7.55	0.0112
Distance x Turns x Elevation	1	33.61	0.01	0.9399
Distance x Turns x Group	1	424.62	0.10	0.7514
Distance x Elevation x Group	1	78.25	0.02	0.8906
Turns x Elevation x Group	1	141176.68	26.49	0.0001
Order	5	2326.46	0.30	0.9082
Order x Distance	5	4357.34	0.73	0.6072
Order x Turns	5	2133.77	0.34	0.8865
Order x Elevation	5	7514.82	2.57	0.0532
Order x Group	5	7157.53	1.32	0.2901
Order x Distance x Turns	5	1457.78	0.40	0.8430
Order x Distance x Elevation	5	1838.36	0.34	0.8807
Order x Distance x Group	5	6047.89	2.91	0.0340
Order x Turns x Elevation	5	11765.53	1.49	0.2308
Order x Turns x Group	5	1589.60	0.28	0.9202
Order x Elevation x Group	5	1493.2542	0.17	0.9718

AA for rooms in the other group (M = -26.06) was significantly less than AA for rooms in the same group (M = 2.58). Figure 52 shows the AA distribution and means for the Group main effect.

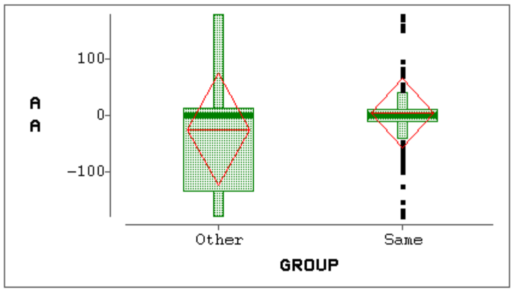


Figure 52. AA as a function of Group for novel routes

Figure 53 shows the AA distribution and means for the Distance x Turns interaction. Two sets of comparisons were made between the means. In the first comparison, means for the 0-turns and 2-turn routes were compared within each distance. At the long distance, AA for rooms separated by 0 turns (M = -26.02) was significantly less than AA for rooms separated by 2 turns (M = 1.92). In the second set of comparisons, means for each distance were compared with 0-turn and 2-turn routes. None of the differences were significant.

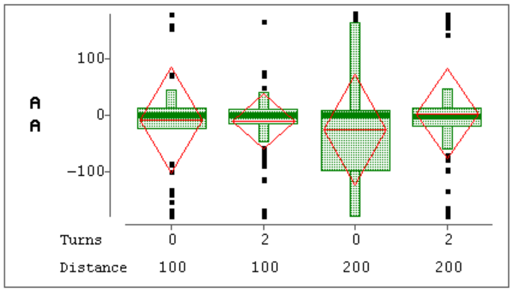


Figure 53. AA as a function of Distance x Turns for novel routes

Figure 54 shows the AA distribution and means for the Distance x Group interaction. Two sets of comparisons were made between the means. In the first comparison, means for the same-group and other-group routes were compared within each distance. At the short distance, AA for rooms in the same group (M = 7.69) was significantly greater than AA for rooms in the other group (M = -29.83). In the second set of comparisons, means for each distance were compared with same-group and other-group routes. None of the differences were significant.

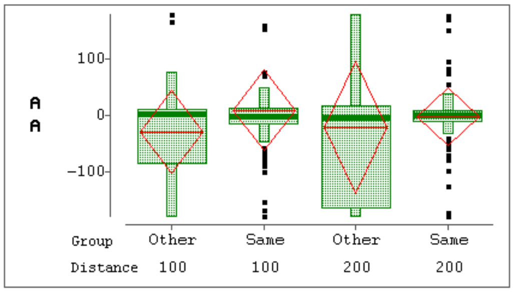


Figure 54. AA as a function of Distance x Group for novel routes

Figure 55 shows the AA distribution and means for the Turns x Group interaction. Two sets of comparisons were made between the means. In the first comparison, means for the same-group and other-group routes were compared within 0-turn and 2-turn routes. For rooms separated by 0 turns, AA for rooms in the same group (M = 13.50) was significantly greater than AA for rooms in the other group (M = -52.19). In the second set of comparisons, means for 0-turn and 2-turn routes were compared with same-group and other-group routes. For rooms in the same group, AA for rooms separated by 0 turns (M = 13.50) was significantly greater than AA for rooms separated by 2 turns (M = -8.95). For rooms in different groups, AA for rooms separated by 0 turns (M = -52.19) was significantly less than AA for rooms separated by 2 turns (M = -0.18).

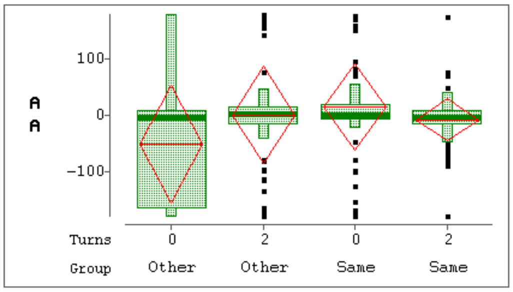


Figure 55. AA as a function of Turns x Group for novel routes

Figure 56 shows the AA distribution and means for the Elevation x Group interaction. Two sets of comparisons were made between the means. In the first comparison, means for the same-group and other-group routes were compared within same-floor and different-floor routes. For rooms on different floors, AA for rooms in the same group (M = 19.18) was significantly greater than AA for rooms in the other group (M = -41.66). In the second set of comparisons, means for same-floor and different-floor routes were compared with same-group and other-group routes. For rooms in the same group, AA for rooms on different floors (M = 19.19) was significantly greater than AA for rooms on the same floor (M = -12.88). For rooms in the other group, AA for rooms on different floors (M = -41.66) was significantly less than AA for rooms on the same floor (M = -11.45).

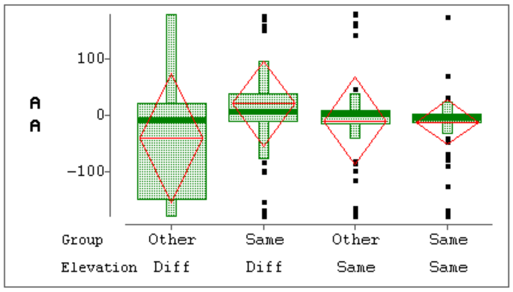


Figure 56. AA as a function of Elevation x Group for novel routes

Figure 57 shows the AA distribution and means for the Turns x Elevation x Group interaction. Three sets of comparisons were made between the means. In the first set of comparisons, means for 0-turn and 2-turn routes were compared within each group and within each elevation. For rooms in the same group but on different floors, AA for rooms separated by 0 turns (M = 43.43) was significantly greater than AA for rooms separated by 2 turns (M = -6.92). For rooms in different groups and on different floors, AA for rooms separated by 0 turns (M = -97.89) was significantly less than AA for rooms separated by 2 turns (M = 8.43).

In the second set of comparisons, means for same-floor and different-floor routes were compared within each group and within 0-turn and 2-turn routes. For rooms in the same group and separated by 0 turns, AA for rooms on different floors (M = 43.43) was significantly greater than AA for rooms on the same floor (M = -14.90). For rooms in different groups and separated by 0 turns, AA for rooms on different floors was significantly less (M = -97.89) than AA for rooms on the same floor (M = -13.58).

In the third set of comparisons, means for same-group and other-group routes were compared within each elevation and within 0-turn and 2-turn routes. For rooms separated by

0 turns and on different floors, AA for rooms in the same group (M = 43.43) was significantly greater than AA for rooms in the other group (M = -97.89).

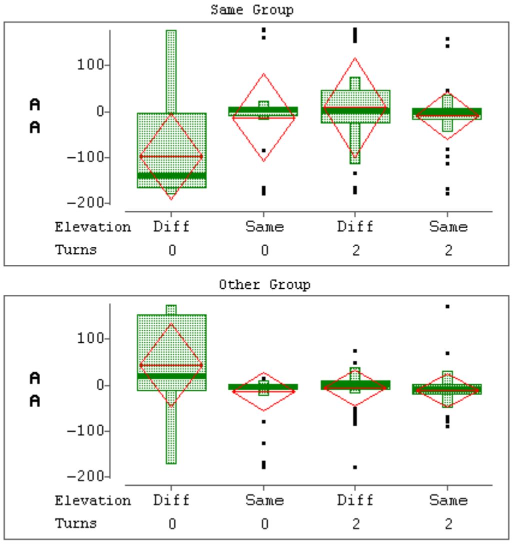


Figure 57. AA as a function of Turns x Elevation x Group for novel routes

Figure 58 shows the AA distribution and means for the Order x Distance x Group interaction. Two sets of comparisons were made between the means. In the first set of comparisons, means for each distance were compared within 0-turn and 2-turn routes within each order. For Order 3, at the short distance, AA for other-group routes (M = -25.96) was significantly less than AA for same-group routes (M = 16.76). For Order 5, at the long distance, AA for other-group routes (M = -41.45) was significantly less than AA for same-group routes (M = 13.47). For Order 6, at the long distance, AA for other-group routes (M = -25.58) was significantly less than AA for same-group routes (M = 22.24). In the second set of comparisons, means for 0-turn and 2-turn routes were compared within each distance within each order. None of the differences were significant.

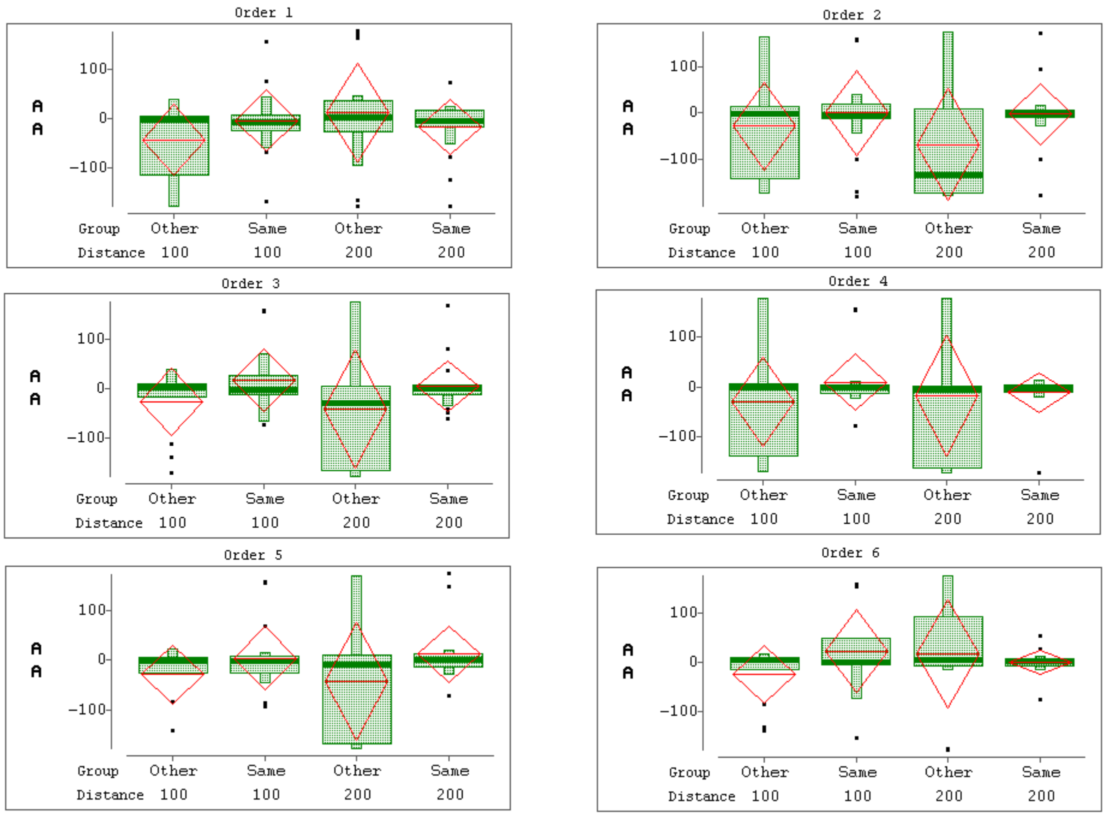


Figure 58. AA as a function of Order x Distance x Group for novel routes

Pointing Task - Elevation Estimation

Known Routes. The table below shows the results of the EA ANOVA for known routes. Distance, Turns, and Floor are the factors describing the target room location in relation to the participant's location when making the distance estimate. Order is the order in which the room pairs were presented. The main effects of Distance and Floor, and the Distance x Floor interaction were significant.

Table 52 ANOVA Results for Pointing Task-Elevation Accuracy for Known Routes

Effect	df	MS	F	Pr > F
Distance	2	1942.11	67.46	0.0001
Turns	1	321.42	3.88	0.0606
Floor	1	17483.74	64.20	0.0001
Distance x Turns	2	19.45	1.08	0.3476
Distance x Floor	2	1875.26	63.64	0.0001
Turns x Floor	1	298.53	3.53	0.0724
Distance x Turns x Floor	2	15.73	0.64	0.5301
Order	5	214.40	0.80	0.5576
Order x Distance	10	27.32	0.95	0.4985
Order x Turns	5	90.97	1.10	0.3875
Order x Floor	5	204.39	0.75	0.5938
Order x Distance x Turns	10	31.69	1.76	0.0949
Order x Distance x Floor	10	29.41	1.00	0.4592
Order x Turns x Floor	5	86.07	1.02	0.4288

Figure 59 shows the EA distribution and means for the Distance main effect. EA for the longest distance (M = 9.97) and the middle distance (M = 7.06) were significantly greater than EA for the shortest distance (M = 2.67). EA for the longest distance was also significantly greater than EA for the middle distance.

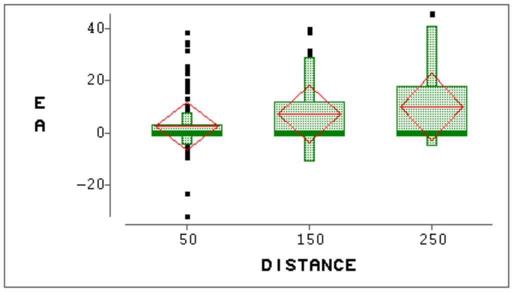


Figure 59. EA as a function of Distance for known routes

Figure 60 shows the EA distribution and means for the Floor main effect. EA for rooms on the second floor (M = 12.35) was significantly greater than EA for rooms on the first floor (M = 0.00).

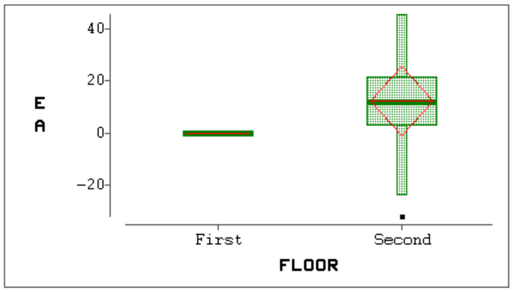


Figure 60. EA as a function of Floor for known routes

Figure 61 shows the EA distribution and means for the Distance x Floor interaction Two sets of comparisons were made. In the first set of comparisons, means for first floor and second floor routes were compared within each distance. For the shortest distance, EA for rooms on the second floor (M = 5.48) was significantly greater than EA for rooms on the first floor (M = 0.00). At the middle and longest distances, the relationship was the same and significant. In the second set of comparisons, means for each distance were compared within first floor and second floor routes. On the second floor, EA for rooms at the longest distance (M = 20.47) was significantly greater than the middle distance (M = 14.39) and shortest distance (M = 5.48).

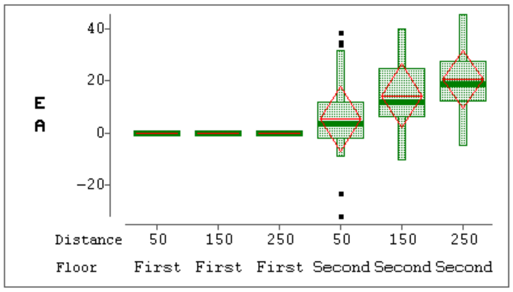


Figure 61. EA as a function of Distance x Floor for known routes

Novel Routes. The table below shows the results of the EA ANOVA for novel routes. Distance, Turns, and Elevation describe the target room location in relation to the participant’s location when making the distance estimate. Group is the target room's semantic group. Order is the order in which the room pairs were presented. The main effects of Distance, Turns, and Elevation, and the Distance x Turns, Distance x Elevation, Turns x Elevation, Distance x Turns x Elevation, and Order x Distance interactions were significant.

Table 53 ANOVA Results for Pointing Task-Elevation Accuracy for Novel Routes

Effect	df	MS	F	Pr > F
Distance	1	2325.27	24.32	0.0001
Turns	1	1651.07	11.86	0.0021
Elevation	1	5245.06	11.59	0.0023
Group	1	299.26	2.77	0.1091
Distance x Turns	1	2422.13	28.68	0.0001
Distance x Elevation	1	1850.58	13.76	0.0012
Distance x Group	1	0.01	0.00	0.9932
Turns x Elevation	1	1544.72	10.31	0.0039
Turns x Group	1	12.01	0.10	0.7567
Elevation x Group	1	373.50	2.73	0.1113
Distance x Turns x Elevation	1	2615.24	22.52	0.0001
Distance x Turns x Group	1	15.68	0.10	0.7510
Distance x Elevation x Group	1	28.13	0.23	0.6402
Turns x Elevation x Group	1	0.01	0.00	0.9935
Order	5	464.57	1.16	0.3583
Order x Distance	5	345.67	3.62	0.014
Order x Turns	5	13.82	0.10	0.9913
Order x Elevation	5	467.62	1.03	0.4207
Order x Group	5	94.39	0.87	0.5134
Order x Distance x Turns	5	73.59	0.87	0.5148
Order x Distance x Elevation	5	228.04	1.70	0.1758
Order x Distance x Group	5	67.84	0.43	0.8236
Order x Turns x Elevation	5	19.46	0.13	0.984
Order x Turns x Group	5	96.93	0.79	0.5657
Order x Elevation x Group	5	89.77	0.66	0.6594

Figure 62 shows the EA distribution and means for the Distance main effect. EA for rooms separated by the long distance (M = 6.83) was significantly greater than EA for rooms separated by the short distance (M = 2.30).

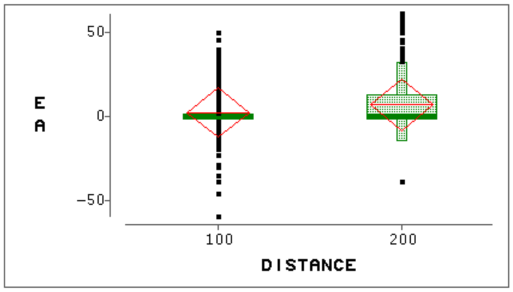


Figure 62. EA as a function of Distance for novel routes

Figure 63 shows the EA distribution and means for the Turns main effect. EA for rooms separated by 0-turns (M = 2.45) was significantly less than EA for rooms separated by the 2-turns (M = 6.90).

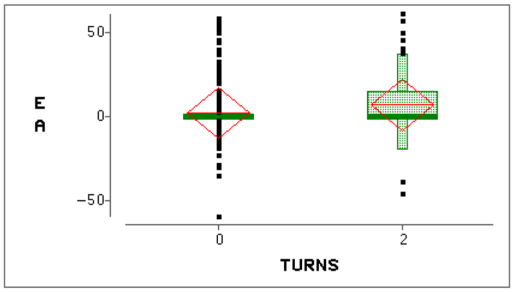


Figure 63. EA as a function of Turns for novel routes

Figure 64 shows the EA distribution and means for the Elevation main effect. EA for rooms on the same floor (M = 0.00) was significantly less than EA for rooms different floors (M = 9.63).

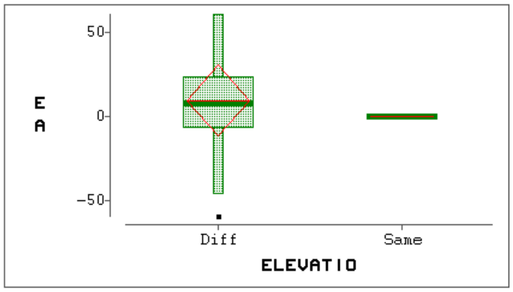


Figure 64. EA as a function of Elevation for novel routes

Figure 65 shows the EA distribution and means for the Distance x Turns interaction. Two sets of comparisons were made. In the first set, EA for 0-turn and 2-turn routes were compared within each distance. At the short distance, EA for 0-turn routes (M = -2.68) was significantly less than EA for 2-turn routes (M = 7.14). In the second set of comparisons, EA for each distance was compared within 0-turn and 2-turn routes. For 0-turn routes, EA for the short distance (M = -2.68) was significantly less than EA for the long distance (M = 6.98).

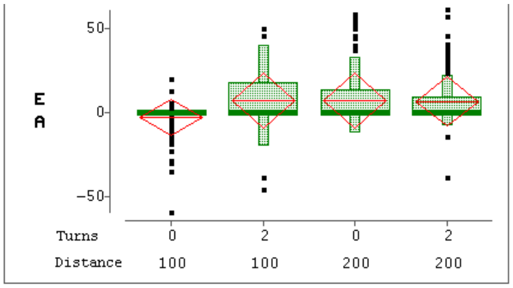


Figure 65. EA as a function of Distance x Turns for novel routes

Figure 66 shows the EA distribution and means for the Distance x Elevation interaction. Two sets of comparisons were made. In the first set, EA for rooms on the same or different floor were compared within each distance. At the long distance, EA for rooms on different floors (M = 14.02) was significantly greater than EA for rooms on the same floor (M = 0.00). In the second set of comparisons, EA for each distance was compared within same-floor and different-floor routes. For rooms on different floors, EA rooms at the short distance (M = 4.80) was significantly less than EA for rooms at the long distance (M = 14.02).

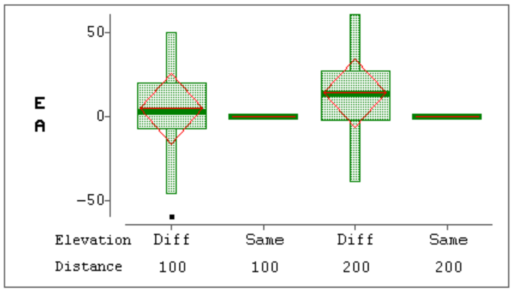


Figure 66. EA as a function of Distance x Elevation for novel routes

Figure 67 shows the EA distribution and means for the Turns x Elevation interaction. Two sets of comparisons were made. In the first set, EA for rooms on the same of different floor were compared within 0-turn and 2-turn routes. For rooms separated by 0 turns, EA for rooms on different floors (M = 5.19) was significantly greater than EA for rooms on the same floor (M = 0.00). For rooms separated by 2 turns, for rooms on different floors (M = 13.99) was significantly greater than EA for rooms on the same floor (M = 0.00). EA In the second set of comparisons, EA for 0-turn and 2-turn routes was compared within same-floor and different-floor routes. For rooms on different floors, EA rooms separated by 2 turns (M = 13.99) was significantly greater than EA for rooms separated by 0 turns (M = 5.19).

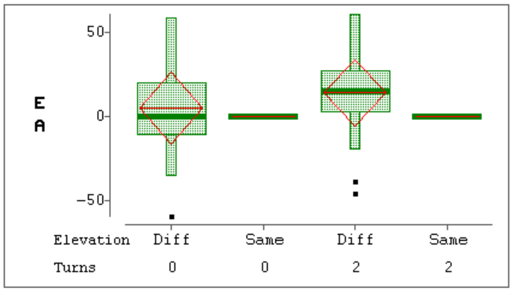


Figure 67. EA as a function of Turns x Elevation for novel routes

Figure 68 shows the EA distribution and means for the Distance x Turns x Elevation interaction. Three sets of comparisons were made. In the first set, EA for 0-turn and 2-turn routes were compared within each distance and elevation. For the shortest distance on different floors, EA for 0-turn routes (M = -5.94) was significantly less than EA for 2-turn routes (M = 14.14). In the second set of comparisons, EA for each distance was compared within turns and elevation. For rooms on different floors separated by 0 turns, EA for the long distance (M = 14.21) was significantly greater than EA for the short distance (M = -5.94). In the third set of comparisons, EA for each elevation was compared within distance and turns. The difference between different floor and same floor routes was significant in all cases.

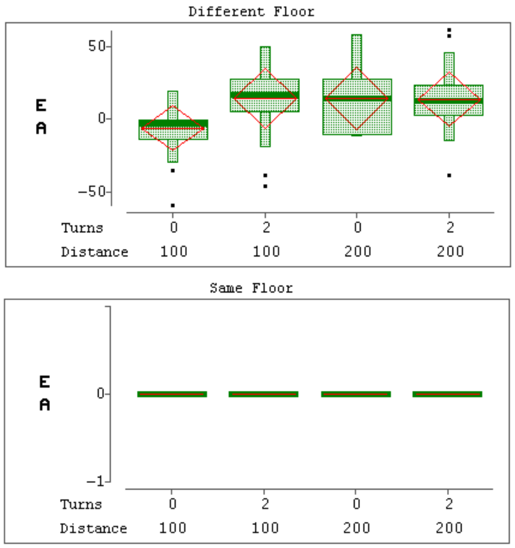


Figure 68. EA as a function of Distance x Turns x Elevation for novel routes

Figure 69 shows the EA distribution and means for the Order x Distance interaction. For Order 2, EA for the long distance (M = 6.10) was significantly greater than EA for the short distance (M = -4.14).

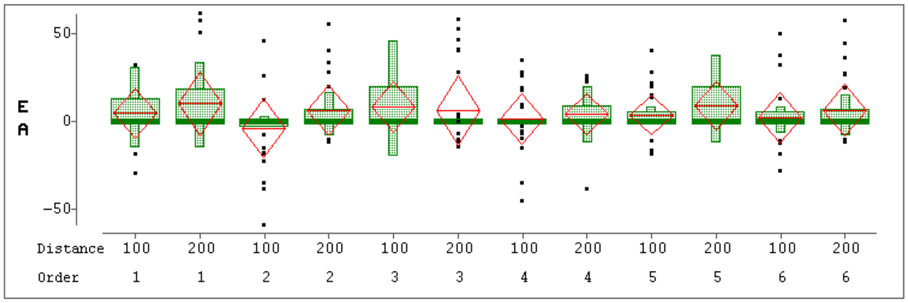


Figure 69. EA as a function of Order x Distance for novel routes

Room Location Decision Task

The table below shows the results of the RT ANOVA for novel routes. Distance, Turns, and Elevation describe the target room location in relation to the participant's location when making the distance estimate. Group is the target room's semantic group. None of the main effects or interactions were significant.

Table 54 ANOVA Results for Room Location Decision (RT) Task for Novel Routes

Effect	df	MS	F	Pr > F
Distance	1	1659996.48	1.42	0.2450
Turns	1	583224.55	0.54	0.4681
Elevation	1	496863.85	0.34	0.5667
Group	1	9078864.33	3.82	0.0624
Distance x Turns	1	1992974.27	1.02	0.3218
Distance x Elevation	1	4184440.99	1.97	0.1736
Distance x Group	1	184993.96	0.17	0.6800
Turns x Elevation	1	2598217.84	1.82	0.1899
Turns x Group	1	263488.32	0.28	0.6008
Elevation x Group	1	3618296.04	1.78	0.1950
Distance x Turns x Elevation	1	474388.22	0.28	0.6012
Distance x Turns x Group	1	332833.52	0.25	0.6234
Distance x Elevation x Group	1	126049.70	0.09	0.7680
Turns x Elevation x Group	1	110791.47	0.08	0.7831
Order	5	8301966.65	0.95	0.4700
Order x Distance	5	864995.84	0.74	0.6010
Order x Turns	5	1847699.32	1.72	0.1678
Order x Elevation	5	1092303.92	0.74	0.5998
Order x Group	5	481634.62	0.20	0.9582
Order x Distance x Turns	5	1022790.00	0.53	0.7548
Order x Distance x Elevation	5	1460863.26	0.69	0.6370
Order x Distance x Group	5	1030988.98	0.97	0.4549
Order x Turns x Elevation	5	519979.23	0.37	0.8671
Order x Turns x Group	5	671231.30	0.72	0.6175
Order x Elevation x Group	5	461284.65	0.23	0.9473

Navigation Task

The table below summarizes the results of the navigation task MANOVA. Wilks' Lambda was used as the multivariate test criterion. The main effects of Turns and Elevation, and the Distance x Elevation, Turns x Elevation, Distance x Turns x Group, and Order x Distance x Elevation interactions were significant.

Table 55 MANOVA Results for Navigation Task for Novel Routes

Effect	Wilks' Lambda	F	Num df	Den df	Pr > F
Distance	0.909335	1.15	2	23	0.3352
Turns	0.631891	6.70	2	23	0.0051
Elevation	0.659979	5.92	2	23	0.0084
Group	0.828449	2.38	2	23	0.1148
Distance x Turns	0.968831	0.37	2	23	0.6948
Distance x Elevation	0.699346	4.73	2	22	0.0196
Distance x Group	0.815762	2.60	2	23	0.0962
Turns x Elevation	0.730047	4.07	2	22	0.0314
Turns x Group	0.987993	0.14	2	23	0.8703
Elevation x Group	0.896591	1.33	2	23	0.2850
Distance x Turns x Elevation	0.913555	0.99	2	21	0.3870
Distance x Turns x Group	0.74548	2.90	2	17	0.0824
Distance x Elevation x Group	0.647933	5.16	2	19	0.0162
Turns x Elevation x Group	0.859414	1.55	2	19	0.2371
Order	0.714087	0.84	10	46	0.5902
Order x Distance	0.730123	0.78	10	46	0.6442
Order x Turns	0.74328	0.74	10	46	0.6874
Order x Elevation	0.595288	1.36	10	46	0.2279
Order x Group	0.519241	1.78	10	46	0.0908
Order x Distance x Turns	0.6969	0.91	10	46	0.5319
Order x Distance x Elevation	0.440504	2.23	10	44	0.0334
Order x Distance x Group	0.753128	0.70	10	46	0.7188
Order x Turns x Elevation	0.575547	1.40	10	44	0.2122
Order x Turns x Group	0.619394	1.24	10	46	0.2893
Order x Elevation x Group	0.534503	1.69	10	46	0.1116

For the significant multivariate tests, univariate ANOVAs, one for each dependent variable, were performed to test the influence of the independent variables on the dependent measures separately. The table below shows the results of the ANOVAs. None of the EED tests were significant. Of the POD tests, The main effects of Turns, Elevation, and the Turns x Elevation and Distance x Elevation x Group interactions were significant.

Table 56 ANOVA Results for Navigation Task for Novel Routes That Were Significant Using the Multivariate Criterion

Effect	DV	Num df	Den df	F	Pr > F
Turns	POD	1	24	6.95	0.0146
	EED	1	24	0.87	0.3600
Elevation	POD	1	24	8.84	0.0066
	EED	1	24	1.98	0.1721
Distance x Elevation	POD	1	23	2.60	0.1202
	EED	1	23	1.56	0.2239
Turns x Elevation	POD	1	23	5.51	0.0278
	EED	1	23	2.42	0.1338
Distance x Elevation x Group	POD	1	20	10.53	0.0041
	EED	1	20	0.69	0.4166
Order x Distance x Elevation	POD	5	23	2.34	0.0742
	EED	5	23	1.11	0.3800

Figure 70 shows the POD distribution and means for the Turns main effect. POD for rooms separated by the 0 turns (M = 3.10) was significantly less than POD for rooms separated by the 2 turns (M = 11.6).

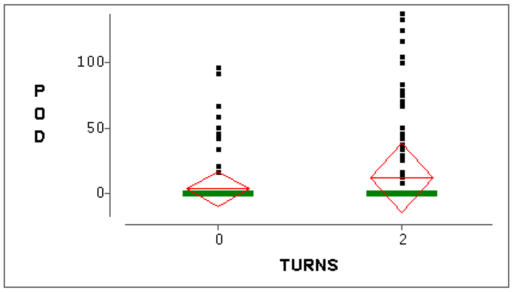


Figure 70. POD as a function of Turns

Figure 71 shows the POD distribution and means for the Elevation main effect. POD for rooms on the same floor (M = 9.73) was significantly than POD for rooms on different floors (M = 4.70).

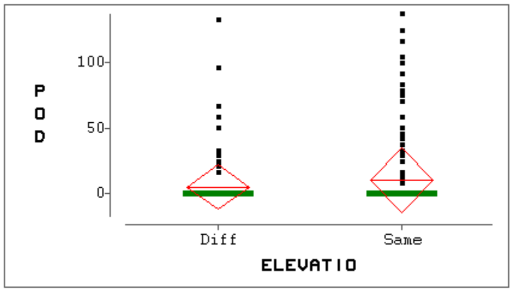


Figure 71. POD as a function of Elevation

Figure 72 shows the POD distribution and means for the Turns x Elevation interaction. Two sets of comparisons were made. In the first set, POD for routes on the same or different floor were compared within 0-turn or 2-turn routes. For rooms separated by 2 turns, POD for rooms on different floors (M = 6.04) was significantly less than POD for rooms on the same floor (M = 17.01). In the second set of comparisons, POD for 0-turn and 2-turn routes was compared within elevation. For rooms on the same floor, POD for rooms separated by 2 turns (M = 17.01) was significantly greater than POD for rooms separated by 0 turns (M = 2.89).

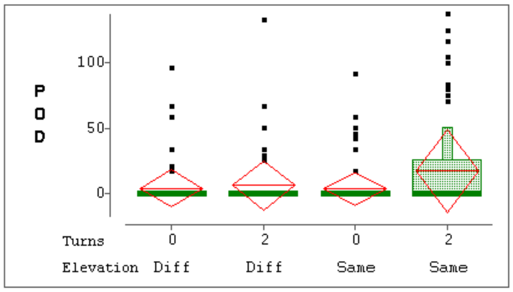


Figure 72. POD as function of Turns x Elevation

Figure 73 shows the POD distribution and means for the Distance x Elevation x Group interaction. Three sets of comparisons were made. In the first set, POD for same-group and other-group routes was compared within distance and elevation. For rooms separated by the short distance and on the same floor, POD for rooms in the same group (M = 14.47) was significantly greater than POD for rooms in the other group (M = 3.77). For rooms separated by the long distance and on the same floor, POD for rooms in the same group (M = 3.04) was significantly less than POD for rooms in the other group (M = 17.31).

In the second set of comparisons, POD for same-floor and different-floor routes was compared within each group and distance. For rooms separated by the short distance and in the same group, POD for rooms on the same floor (M = 14.47) was significantly greater than POD for rooms on a different floor (M = 1.89). For rooms separated by the long distance and in the same group, POD for rooms on the same floor (M = 17.31) was significantly greater than POD for rooms on a different floor (M = 4.32).

In the third set of comparisons, POD for each distance was compared within each group and elevation. For rooms in the same group on the same floor, POD for rooms separated by the short distance (M = 14.47) was significantly greater than POD for rooms separated by the long distance (M = 3.04). For rooms in different groups on the same floor, POD for rooms separated by the short distance (M = 3.78) was significantly less than POD for rooms separated by the long distance (M = 17.31).

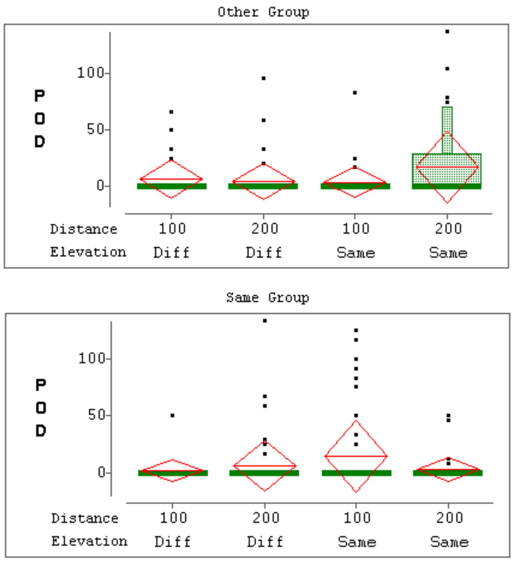


Figure 73. POD as function of Distance x Elevation x Group

Comparison of Memory for Known and Novel Routes

To determine if the participants' memory for known or novel routes was more accurate, the effect of route type was analyzed using separate ANOVAs for DEA, AA, and EA.

The table below shows the results of the DEA ANOVA. Neither the main effect nor the interaction was significant.

Table 57 Comparison of Route Types ANOVA Results for DEA

Effect	df	MS	F	Pr > F
Route Type	1	32.33	0.02	0.8893
Route Type x Turns	1	1412.41	0.74	0.3967

Table 15 shows the results of the AA ANOVA. The main effect was significant. AA for known routes (M = 2.31) was significantly greater than AA for novel routes (M = -11.45). Figure 74 shows the AA distribution and means for the main effect of route type.

Table 58 Comparison of Route Types ANOVA Results for AA

Effect	df	MS	F	Pr > F
Route Type	1	36827.10	10.02	0.0042
Route Type x Turns	1	12103.51	2.83	0.1057

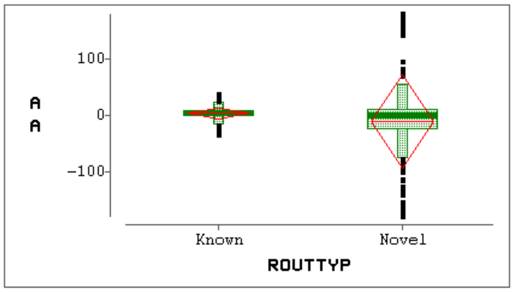


Figure 74. AA as a function of Route Type

The table below shows the results of the EA ANOVA. Neither the main effect or interaction was significant.

Table 59 Comparison of Route Types ANOVA Results for EA

Effect	df	MS	F	Pr > F
Route Type	1	846.69	3.65	0.0682
Route Type x Turns	1	29.03	0.34	0.5644

Note: The Distance x Route Type interaction cannot be tested because the three distances for known routes are different from the two distances for novel routes. The Floor x Route Type interaction cannot be tested because the Floor variable does not apply to novel routes. The Elevation x Route Type and Group x Route Type interaction cannot be tested because the Elevation and Group variables do not apply to known routes.

Summary of Post Learning Trial Measurements

The table below summarizes the results of the analysis of the post-learning trials tests. In the analysis of knowledge about known routes, all of the main effects were significant in one or both of the tasks. However, all but one of the main effects was also present in a significant 2-way interaction. Only the main effect of Floor, in the pointing task, did not enter into a significant 2-way interaction. In contrast, all of the significant main effects were also involved in significant 2-way or 3-way interactions. Among the tasks used to test knowledge of the VE, the room location decision task failed to produce any significant effects. In the navigation task, EED did not produce any significant effects.

Table 60 Summary of Significant Effects in Analysis of Post-Learning Trials Tests

	Route Type and Dependent Measure								
	Known			Novel					
Effect	DEA	AA	EA	DEA	AA	EA	RT	POD	EED
D		✓	✓			✓			
T	✓					✓		✓	
F	✓	✓	✓						
E				✓		✓		✓	
G					✓				
D x T	✓	✓			✓	✓			
D x F	✓		✓						
D x E						✓			
D x G					✓				
T x F	✓								
T x E						✓		✓	
T x G					✓				
E x G					✓				
DxTxF									
DxTxE						✓			
DxTxG									
DxExG								✓	
TxExG					✓				

Note: A ✓ indicates a significant effect at $\alpha = .05$. In the Effect column D = Distance, T = Turns, F = Floor, E = Elevation, G = Group.

While the ANOVAs used to analyze the post-learning data included three-way interactions as part of their analysis models, these interactions are not discussed further. In this experiment, a three-way interaction describes a single pair of rooms. A significant three-way interaction indicates that the memory for the route between one pair of rooms is different than the memory for the route between another pair of rooms. Comparison of two routes does not help draw conclusions about the overall effects of the independent variables on memory for the VE.

Discussion

Navigation Performance During Learning Trials

In the learning trials, participants were given the room name and number during the first two trials. In the remaining four trials, they were given the room name only. The room number indicated the room’s floor (first or second) and the relative distance of the room from the wall closest to the starting-point. Participants were told that they would be given the room number during the first trial only and that they should try to remember a room’s location based on its name rather than its number. This section discusses the patterns of results that could be found in the analysis of the learning-trials data and the interpretation of those patterns.

Two measures of navigation performance were collected during each trip: POD and EED. POD is a measure of the total distance traveled as a percentage of the optimal distance. A POD greater than 0 means the participant traveled farther than necessary to reach the room. As POD increases, one can conclude that the participant is less sure of the target-room’s location. EED is a measure of the distance traveled on the wrong floor as a percentage of the total distance traveled. An EED greater than 0 indicates that the participant went to the wrong floor when searching for the target room. As EED increases, one can conclude that the participant is less sure which floor the room is on.

As EED is a percentage of POD, they are moderately correlated. An EED greater than 0 indicates a POD greater than 0. However, a high EED does not always imply a high POD.

Given the two dependent variables, there were three possible outcomes, as shown in the table below.

Table 61 Possible Patterns of POD and EED Scores

POD	EED
0	0
> 0	0
> 0	> 0

If both POD and EED equal zero, the participant knew the floor, distance, and whether there were turns on the route to the target room. If POD is greater than zero but EED equals 0, the participant knew the room's floor but was unsure about the distance and the number of turns on the route to the target room. If POD and EED are greater than zero, the participant did not know the room's floor and may not have known the distance or the number of turns on the route to the target room. It is possible that POD and EED are greater than zero and the participant knew the distance and number of turns on the route to the target room. The experimenter observed, particularly in the fifth trial, participants traveling to the right location on the wrong floor while searching for a room. For example, if the participant was searching for Potatoes, they would travel to Oranges, upon arriving at Oranges they would realize they were on the wrong floor. They would turn around, return to the starting-point, and travel directly to Potatoes. In these trips, the pattern of results was $0 < POD <= 200\%$ and $0 < EED <= 67\%$.

The POD and EED data were analyzed using a MANOVA. If the overall MANOVA was significant, the effects of the independent variables on POD and EED were evaluated separately. As shown in the table below, there were four possible outcomes in the analysis.

Table 62 Possible Patterns of ANOVA Results Following a Significant MANOVA

POD	EED
Non-significant	Non-significant
Non-significant	Significant
Significant	Non-significant
Significant	Significant

If the POD ANOVA and EED ANOVA were significant, the independent variables affected the overall difficulty of learning the room's location and the room's floor. Conversely, if neither the POD and EED ANOVAs were significant, the significance of the MANOVA was the result of the effects of the independent variables on a combination of POD and EED but there were no differences in either POD and EED separately.

If the POD ANOVA was significant but the EED ANOVA was not significant, the independent variables affected the overall difficulty of learning a room's location but did not affect the difficulty of learning the correct floor. A non-significant EED ANOVA does not mean that confusion about a room's floor did not contribute to the difficulty of learning a room's location.

If the POD ANOVA was not significant and the EED ANOVA was significant, the independent variables affected the participants' learning the correct floor but did not affect the overall difficulty of learning the correct location. A non-significant POD ANOVA does not mean that finding the rooms was not difficult.

The remainder of this section discusses the learning that occurred over trials. Most of the discussion addresses the participants' navigation performance while searching for the target room since this is the leg of each trip which exhibited the greatest variability.

Navigation Performance while Searching for the Target

This section is divided into several subsections. This section discusses the overall pattern of POD and EED results. The next three sections describe the effects of the independent variables on navigation performance across all trials. Both the main effects and the two-way interactions are considered in the interpretation of the results. The last section summarizes the pattern of results across individual trials.

While the MANOVA included three-way interactions as part of the analysis model, these interactions are not discussed below because the combination of three factors describes the location of individual rooms. For example, a Distance x Turn x Floor interaction creates 12 cells (3 distances X 2 turns X 2 floors) with one room per cell. A significant three-way interaction indicates that the participants had more difficulty learning the location of one room than another. This is not surprising. Nor is it helpful in drawing conclusions about the effects of the independent variables based on the comparative difficulty of learning the location of two rooms.

The POD data show that participants were able to use the room numbers effectively on the second trial but not on the first. During the first trial, the participants were probably learning the numbering scheme while learning the layout of the virtual environment. In the second trial, they were able to use the room numbers to navigate quickly and accurately to the target rooms. In the third trial, removal of the room numbers raised POD beyond the level of the first trial (as shown in the figure below). Participants traveled, on average, 25% farther than necessary on the third trial. POD dropped from the third to the sixth trial. By the fifth trial, it was below the level of the second trial, i.e., participants performed better in the fifth trial without the room numbers than in the second trial when they had the room numbers.

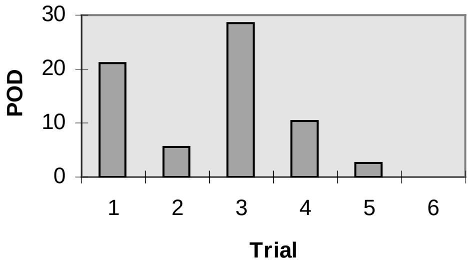


Figure 75**.** Average POD for all trips

The figure below shows the number of trips in which POD was greater than zero (i.e., participants did not travel the shortest route) and the average POD for those trips. On those trips in which POD was greater than zero, POD remained fairly constant. The decrease in POD across trials, shown in Figure 75, resulted from a decrease in the number of trips in which POD was greater than zero rather than a decrease in POD. In other words, when participants made navigation errors and their route was longer than the shortest route, the extra distance traveled stayed fairly constant across trials 3, 4, and 5. The decrease in average

POD across trials (shown in Figure 75) reflects the decrease in the number of trips in which POD exceeded zero.

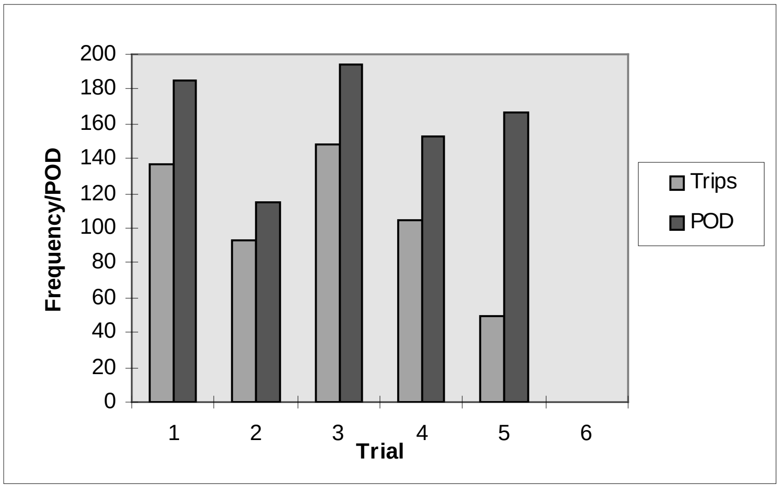


Figure 76. Number of trips in which POD was greater than 0 and average POD for those trips

The EED data show a slightly different trend. As expected, EED was near 0 during the first two trials when the participants were given the room number. The figure below shows that EED jumped to approximately 3.5% during the third trial and decreased on the following trials.

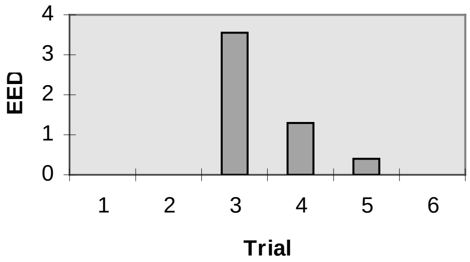


Figure 77. Average EED for all trips

The figure below shows that the number of trips to the wrong floor decreased from the third to the fifth trial. However, the average distance traveled on the wrong floor stayed constant across trials 3 through 5. The decrease in average EED resulted from a decrease in the number of trips to the wrong floor rather than a decrease in the distance traveled on the wrong floor once the participants went there.

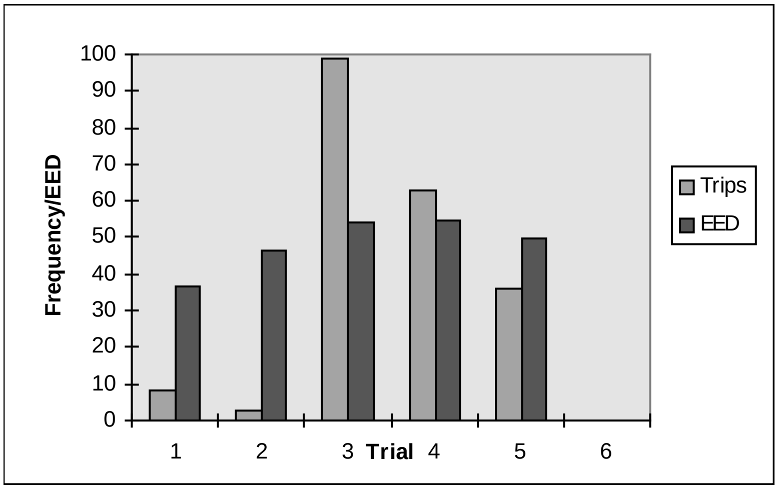


Figure 78. Number of trips in which EED was greater than 0 and average EED for those trips

While the magnitude of EED may seem large, even in the fifth trial, in most trips in the fourth and fifth trial, a high EED indicates that the participant knew the location of the room, in terms of distance and turns, but did not know which floor the room was on. For example, if the target room was Potatoes, the participant might go to Oranges, which is in the same location as Potatoes, as defined by distance and turns, but on the wrong floor. If the participant traveled to Oranges, back to the starting-point and then to Potatoes, EED would be 67%.

The figure below shows the relationship between the number of trips during which the participants traveled to the wrong floor and the number of trips in which POD was greater than zero. In trials 3, 4, and 5, it appears that over half the trips involving errors involved elevation errors. In other words, in over 60% of the trips in which participants did not travel the shortest route, they also went to the wrong floor. This suggests that the room’s floor is an integral part of the memory for a room’s location. Learning the room's floor was probably the last part of the room's location that was learned. If the room's floor was learned before the distance or number of turns, the ratio of the number of trips in which EED was greater than 0 to the number of trips in which POD was greater than 0 would steadily decrease from trial 3 to trial 5.

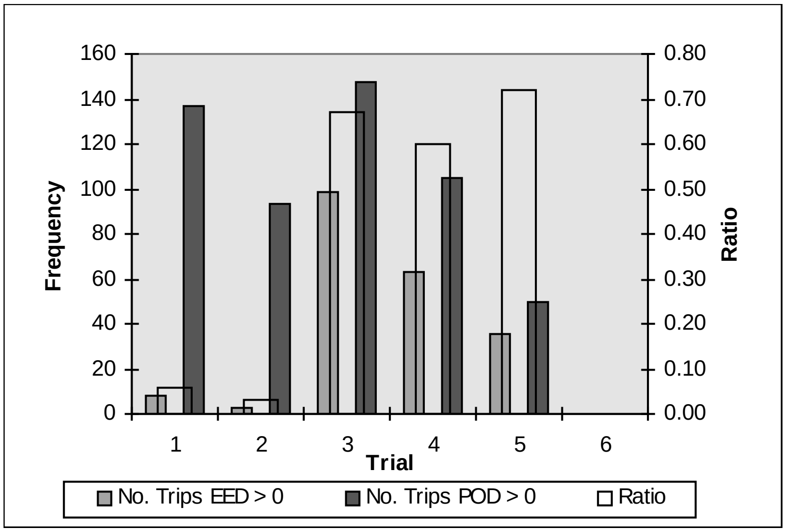


Figure 79. Number of trips in which EED was greater than 0, POD was greater than 0 and ratio of these two numbers

Effects of Distance on Learning. The effect of distance, across all trials, showed that the location of rooms that were at the middle or longest distance were more difficult to learn than the rooms at the shortest location. When searching for rooms at the middle and longest distance, participants traveled farther and traveled farther on the wrong floor than when searching for rooms at the shortest distance.

The distance effect was modified by the number of turns. When the route to a room had 0 turns, participants traveled farther when searching for a room at the middle distance than when searching for a room at the shortest distance. When the route to a room had 2 turns, participants traveled farther when searching for a room at the middle or longest distance than when searching for a room at the shortest distance.

The distance effect was also modified by the room's floor. On the first floor, the effect of distance was clear. The locations of the rooms farthest from the starting-point were the most difficult to learn. The locations of rooms at the middle distance were the next most difficult to learn. The locations of rooms closest to the starting-point were the easiest to learn. On the second floor, the effect of distance was slightly different. The locations of rooms at the middle distance were the most difficult to learn. There was no difference between the closest and farthest rooms.

<u>The Effect of Turns on Learning</u>. The effect of turns, across all trials, showed that when the route to a room had 2 turns, participants traveled farther than when the route had 0 turns. This was true at all distances and on both floors. The number of turns did not affect the distance traveled on the wrong floor. This suggests that the number of turns, on the route from the starting-point to the room, affects the overall difficulty of learning a room's location but does not affect the learning of the room's floor.

The Effects of Floor on Learning. The effect of floor showed that learning a room was on the first floor was more difficult than learning a room was on the second floor. Participants searching for a room on the first floor traveled farther on the second floor than participants searching for a room on the second floor traveled on the first floor. This floor effect held for rooms at the shortest and longest distance from the starting-point. There was no difference for rooms at the middle distance.

For rooms at the middle distance, the overall difficulty of learning their location was easier for first-floor rooms than for second-floor rooms. In contrast, the overall difficulty of learning the location of rooms farthest from the starting-point was easier when the rooms were on the second floor than when they were on the first floor.

The number of turns on the route to a room also affected the floor effect. When the route to a room had 0 turns, the overall difficulty of learning the room's location was easier when the room was on the second floor than when it was on the first floor. When the route to a room had 2 turns, the opposite was true.

Learning During Individual Trials. This section discusses the effects of the independent variables on learning across all trials. Rather than discuss the results for each block of trials, this section discusses the pattern of results across individual trials.

Distance had an effect after the participants were not given the room number. In trials 3, 4, and 5, the location of rooms at the shortest distance were easier to learn than the location of rooms at the middle and longest distance. In some trials, the middle distance rooms were the most difficult to learn. The distance of the route to a room also affected the distance traveled on the wrong floor. Participants traveled less on the wrong floor when the rooms were at the shortest distance than at the middle or longest distance.

Turns had a consistent effect on all trials. When the route to a room had 0 turns, participants had less difficulty learning the room’s location than when the route had 2 turns.

Floor also had an effect after the participants were not given the room number. In all trials, participants had more difficulty remembering a first-floor room was on the first floor than remembering a second-floor room was on the second floor.

The interaction of the number of turns and the floor showed that the difference in the difficulty of learning a room’s location, as affected by the number of turns, was only significant on the second floor. When participants were searching for rooms on the first floor, the number of turns on the route to a room had no effect on the distance traveled while searching for the room.

The interaction also showed that the overall difficulty of learning a room’s location was only affected by the room’s floor when the route to the room had 0 turns. When the route had 2 turns, the room’s floor had no effect on the difficulty of learning the room’s location.

Navigation Performance while Returning to the Starting Point

The analysis of the Back data showed that the distance from the room to the starting-point and the number of turns on the route to the starting-point affected navigation performance. This was unexpected because none of the participants had difficulty returning to the starting-point after finding a room. It appears that the significant effects are the result of participants' attempts to return to the staring point as quickly as possible. Several participants, when traveling to Squash, Asparagus, and Cherries, would take the shortest route to the room. However, their route back was not the shortest route because they decided that turning back toward the starting-point, while in front of the room, was not the fastest route back to the starting-point. Instead, they continued past the room and turned back toward the main corridor, as shown in the figure below. This allowed them to keep moving, thereby eliminating the need to stop, turn, and start on the route back to the starting-point. Their strategy reduced the amount of time taken to return to the starting-point even though their route was not the shortest possible route.

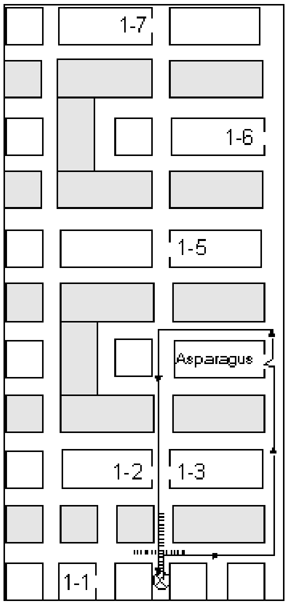


Figure 80**.** Faster but longer route from room to starting-point

Memory for the VE After the Learning Trials

Tests of Spatial Memory

Following the learning trials, participants performed four tasks which measured their knowledge of room location in the virtual environment. The four tasks were (a) a route-distance-estimation task, (b) a pointing task, (c) a room-location-decision task, and (d) a navigation task.

In both the route-distance and direction-estimation tasks, participants were presented with either room-room or starting-point-room pairs. The room-room pairs required estimates of distance and direction along routes that were not part of the learning trials, i.e., they were novel routes. These pairs were intended to assess the participants' survey knowledge of the VE. The starting-point room pairs required them to provide estimates, of distance or direction, along the routes used in the learning trials, i.e., they were known routes. These pairs were intended to assess the participants' route knowledge of the VE.

In the room-location-decision task, participants were presented with a prime and then a target room. They had to decide if the target room was on the same floor as the prime. The task was intended to reveal the structure of spatial memory for the VE. The prime-target pairs were the same room-room pairs used in the route-distance-estimation and direction-estimation tasks.

The navigation task was intended to determine if (a) route knowledge of the VE, gained through the learning trials, can be translated into efficient navigation on novel routes, and (b) navigation relies on the same memory structure and processes as the other three tasks. All of the routes used in the navigation task were novel room-room routes.

Interpretation of Results

Several researchers (Hirtle & Jonides, 1985; McNamara, 1986; Hirtle, 1995) propose that environmental knowledge is stored in a hierarchical or partially hierarchical form. In hierarchical models, higher levels of the hierarchy contain less detailed knowledge than lower levels. As one progresses farther down the hierarchy, each node represents a smaller part of the environment. Hierarchical clusters are formed by semantic grouping of locations/objects/buildings and by environmental characteristics. Previous research (Hirtle & Jonides, 1985) suggests that hierarchies are formed by prominent changes in the physical environment (e.g., elevation changes), human-made structures (e.g., roads), or by meaningful groupings of objects in the environment (i.e., non-spatial characteristics influence the formation of hierarchies).

If the participants' environmental knowledge of the VE was hierarchical and integrated both spatial and non-spatial knowledge, one form the hierarchy could take is shown in the figure below. This hierarchical structure is based on several assumptions:

- Elevation is the dominant environmental characteristic.
- The rooms on each floor will be associated by semantic group membership.
- The stairs and starting-point will be a reference point that is separate from the rooms on either floor.

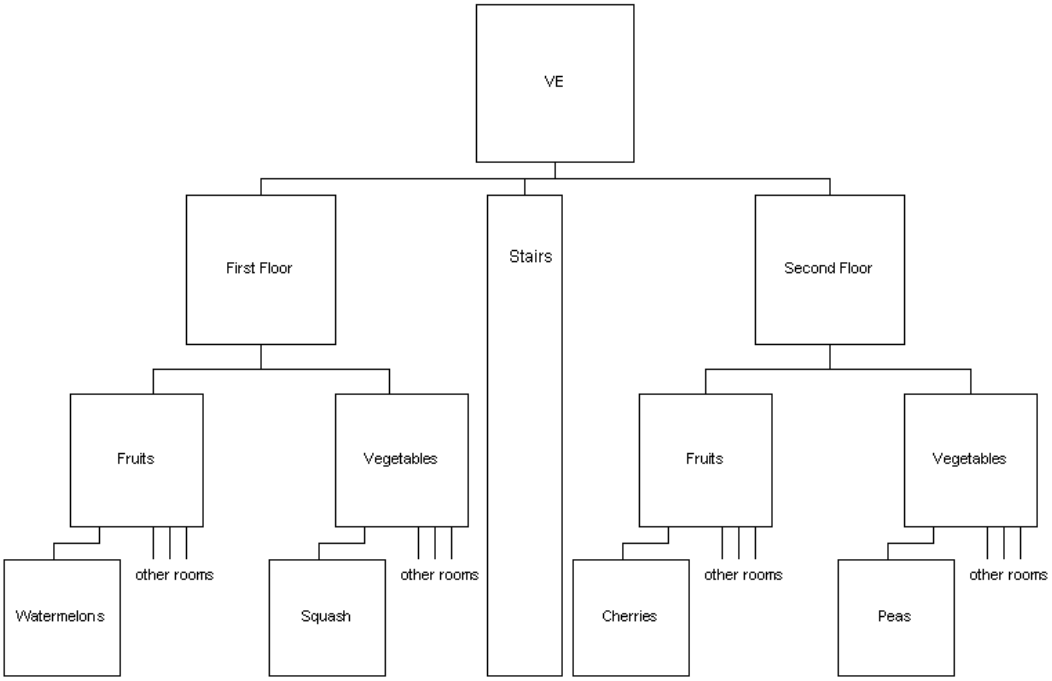


Figure 81. Hierarchical structure of environmental knowledge with integrated spatial and non-spatial knowledge

It was expected that the rooms on the same floor would be more closely associated in memory than rooms on different floors. The hierarchical structure implies that some rooms are more closely associated in memory than other rooms. As one moves farther down the hierarchy, rooms are more closely associated. For example, Cherries and Grapes (Grapes is a room on the second floor) would be more closely associated than Cherries and Peas. Yet Cherries and Peas are more closely associated than Cherries and Watermelons. The differences in associative strength may distort memory of the VE.

Based on this hierarchy, one can predict patterns of responses for each of the post-learning dependent measures. In the route-distance-estimation task, one would expect a distortion of distance estimates for rooms in different hierarchical groups in comparison to rooms in the same hierarchical group. For example, the distance between Squash and Peas would be overestimated while the distance between Squash and Watermelons would be underestimated. Direction estimates for rooms within the same hierarchical group would be more accurate than direction estimates for rooms in different groups. Reaction time, in the room-location-decision task, should be less for rooms within the same hierarchical group.

The hierarchical structure was not expected to influence performance on the navigation task. If navigation relies on the same memory structure and processes as the other three tasks, the pattern of effects of the independent variables should be similar across all the tasks. It was not expected that this would be the case. Most likely, navigation utilizes visual cues, e.g., room names and numbers, that were not available during the other tests of memory for the VE.

Assessment of Support for Hypotheses

The next two sections describe the support (or lack thereof) for the research hypotheses. Table 61 summarizes the support for the hypotheses.

Table 63 Summary of Support for Hypotheses

		Dependent Variable					
Independent Variable	Hypothesis	DEA	AA	EA	RT	POD	EED
Group	H1	N					
	H2		P	Y			
	H3				N		
	H4					Y	
	H5						Y
Elevation	H6	P					
	H7		N				
	H8			Y			
	H9				N		
	H10					N	
	H11						N
Distance	H12	N					
	H13		P				
	H14			P			
	H15				N		
	H16					N	
	H17						N
Turns	H18	P					
	H19		N				
	H20			P			
	H21				N		
	H22					P	
	H23						N

NOTE: N = No support, P = Partial support, Y = Full Support. H2, H4, and H5 were null hypotheses.

As shown in the table, all of the dependent measures, except RT, were affected by at least one of the independent variables thereby providing partial or full support for the hypotheses associated with the independent variables. The following section discusses the failure of the independent variables to affect performance on the room-location-decision task.

Room-Location-Decision Task. None of the hypotheses associated with the room-location-decision task (H3, H9, H15, H21) received any support from the results of this experiment. Since the other dependent variables were affected by the independent variables, one could conclude that spatial memory was affected by the independent variables. Based on the results of McNamara (1986), Merrill and Baird (1987), McNamara, Halpin, and Hardy (1992), one would expect that RT, in the room-location-decision task, would be affected by spatial and non-spatial characteristics of the environment. For example, McNamara (1986) found that spatial boundaries affect RT. In his experiment, RT was faster when the prime and the target were in the same spatial region than when they were in different spatial regions.

In contrast to McNamara's results, RT was not affected by spatial characteristics of the environment. Neither the route distance nor the number of turns on the route between the prime and the target, nor the similarity or difference in elevation between the prime and the target affected RT. As shown in the table below, the RTs were uniform for the levels of the four independent variables.

Table 64 Mean RT in Room-Location-Decision Task for Each Level of the Four Independent Variables

IV	Level of IV	RT
Group	Same	2209 ms
	Different	1985 ms
Elevation	Same	2030 ms
	Different	2174 ms
Distance	Close	2153 ms
	Far	2050 ms
Turns	0	2148 ms
	2	2050 ms

One explanation for the difference in results can be found in the differences in RT between the previous research and this experiment. The table below shows the mean RTs from two of the previous experiments and this experiment. In each case, the independent variable was the physical distance between the prime and the target.

Table 65 Comparison of Mean RTs

	Distance between Prime and Target	
Experiment	Close	Far
McNamara (1986)	734 ms	778 ms
McNamara, Halpin, & Hardy (1992)	876 ms	988 ms
Barlow (this research)	2153 ms	2050 ms

The room-location-decision task was intended to reveal the structure of spatial memory for the VE. However, the structure of spatial memory will only affect RT if the participants respond quickly and their responses are not influenced by some type of problem-solving strategy. In other words, if the participants' responses are not "immediate", the results probably do not reflect the structure of spatial memory. It is apparent that participants in this experiment responded much more slowly than participants in the previous experiments. It is probable, due to the longer RTs, that RT in this experiment does not reveal the structure of spatial knowledge.

A likely explanation for the lack of effect of the independent variables on RT, lies in the instructions provided to the participants. The participants were told to respond as quickly as possible but to try to provide no more than one wrong response out of 16 trials. Most participants attained this level of accuracy. Typically, instructions for RT experiments instruct participants to respond “as quickly and as accurately as possible.” The table below shows the mean percentage of erroneous responses, by participant, for each of the three experiments.

Table 66 Comparison of Mean Error Percentages

Experiment	Mean Percentage of Trials with Incorrect Responses
McNamara (1986)	12%
McNamara, Halpin, & Hardy (1992)	18%
Barlow (this research)	6%

It appears that participants in this experiment sacrificed speed for accuracy, in comparison to the participants in the previous research. In their attempt to attain the desired level of accuracy described in the task instructions, participants responded so slowly that the cognitive processes associated with preventing errors were the primary determinant of their RT.

Independent Variables and Hypotheses

This section describes each independent variable and the hypotheses associated with it. This description is followed by a summary and interpretation of the results that pertain to the hypotheses.

Group. The room names were either the name of a fruit or vegetable. Group was the independent variable describing the semantic group membership of the room name. The purpose of creating two semantic groups was to investigate the integration of non-spatial knowledge into the participants spatial memory of the VE. Since the fruit names were assigned to rooms on one side of the main hallway and vegetable names were assigned to rooms on the other side of the hallway, it was expected that participants would form groups based on non-spatial information, i.e., room name group membership. Membership in these groups would be the basis for distortions in spatial memory. If Group affected performance on spatial tasks, e.g., route-distance-estimation, then one could conclude that non-spatial information has been integrated into spatial memory. The following paragraphs discuss the support for the hypotheses involving non-spatial information and the anticipated Group effects.

> H1: Route-distance estimates will be larger when the origin and target are in different semantic groups than when the origin and target are in the same semantic group.

Participants underestimated the distance between rooms in the same semantic group and between rooms in different semantic groups. The results of this experiment provide no support for the hypothesis that non-spatial knowledge affected the accuracy of the participants' distance estimates.

> H2: Direction estimates for origin-target pairs from different semantic groups will be of equal accuracy, in elevation and azimuth, as estimates for origin-target pairs from the same semantic group.

The AA data for novel-route pairs provided partial support for the hypothesis. In all but two conditions, AA for same-group pairs was no different than AA for other-group pairs. AA was more accurate for same-group pairs when the rooms were separated by the shorter distance. AA was more accurate for same-group pairs for rooms separated by 0 turns.

The analysis of the EA data supported the hypothesis. There were no differences in EA as a function of semantic group membership.

> H3: When making a decision about a room location, the participant's RT will be shorter when the prime and the target are in the same semantic group than when they are in different semantic groups.

The results did not support the hypothesis. There was no difference in RT between the same-group and other-group pairs.

> H4: Navigation on routes whose origin and target are in the same semantic group will take the same amount of time as navigation on routes whose origin and target are in different semantic groups.
>
> H5: The number of elevation navigation errors on routes whose origin and target are in the same semantic group will be the same as the number of elevation navigation errors on routes whose origin and target are in different semantic groups.

The results of the analysis of the POD and the EED data supported the hypothesis. There was no difference in POD or EED between same-group and other-group pairs.

Relationship to Previous Research. Hirtle and Jonides (1985) found that distance estimates for distances between locations in different subjective (non-spatial) groups, were greater than estimates for equal-length distances between locations in the same subjective group. Hirtle and Mascolo (1986) found similar results. Their results suggest that the subjective groups formed by participants affect judgments about the spatial relationship between locations by

(1) exaggerating inter-group distances, and (2) attenuating intra-group distances. Their results suggest that spatial processing is the function of spatial and non-spatial components.

In contrast, the results of this experiment do not suggest that non-spatial information affects performance on spatial tasks. Group membership had no effect on the accuracy of the route distance estimates. AA was affected by Group membership in only two instances. There are two differences between the groups used in previous research and Group in this experiment.

First, Hirtle and Jonides (1985) used subjective groups that already existed in their participant's memory for their college's campus. Navigation through the campus, over a period of months or years, contributed to the formation of these groups. In assessing their participants' memory, Hirtle and Jonides were able to identify existing subjective groups and use locations in these groups in their distance-estimation task. In comparison, the effect of Group in this experiment relied on the formation of fruit and vegetable groups during the experiment. Similar to Hirtle and Jonides, participants should have acquired the non-spatial information while navigating through the environment. However, unlike Hirtle and Jonides, the groups' presence was not confirmed during this experiment. Based on the results, one could argue that the groups do not exist.

The other difference lies in what Merrill and Baird (1987) refer to as "functional" relationships among locations. Merrill and Baird's research showed that non-spatial information does not affect spatial tasks when the non-spatial information is the only source of similarity or differences between locations. In other words, if the fruit and vegetable names were randomly assigned to rooms, one would not expect that Group would have any effect. One would only expect an effect if the room names and spatial characteristics combined to form subjective groups. (The VE used in this experiment supported the formation of groups by placing fruit and vegetable rooms on opposite sides of the main hallway on each floor.) In addition, the integration of non-spatial (room name) and spatial information will only occur when the non-spatial information promotes a functional relationship among locations. Within the context of a college campus, buildings containing similar departments or administrative bodies might be located near each other. The physical proximity of the buildings combines with the functional proximity to create spatial groups. In the VE, the membership of room names in the fruit or vegetable group, may not have been strong enough to form functional relationships among rooms in the same Group. In the absence of a functional relationship, non-spatial information had no effect on spatial tasks.

It was not expected that Group membership would affect performance on the navigation tasks since navigation can use environmental cues that are not available during the memory tasks. Even if Group membership affected spatial memory, its effect may be canceled by the presence of navigational cues provided by the VE.

Elevation. The VE had two floors. Elevation was the independent variable describing the relationship between the origin-destination or prime-target room pairs. The two rooms were either on the same floor or on different floors. It was expected that the rooms on the same floor would be more closely associated in memory than rooms on the other floor. As shown by several researchers (e.g., McNamara, 1986; Sadalla, Burroughs, & Staplin (1980)) physical boundaries create subjective groupings of locations. One subjective group should contain the rooms on the first floor. The other subjective group should contain the rooms on the second floor. If the difference or similarity of elevation in the room pairs affected the participants' performance on the post-learning-trials tasks, then one could conclude that elevation is part of spatial memory. This section discusses the hypotheses related to Elevation and the support for the hypotheses provided by the results of this research.

> H6: Route-distance estimates for origin-target pairs that are on different floors will be less accurate than for origin-target pairs that are on the same floor.

DEA data for known routes did not support the hypothesis. Memory for route-distance to second-floor rooms was more accurate than memory for route-distance to first-floor rooms. This difference was significant for rooms at the shortest and longest distance only. For rooms at the middle distance, there was no difference in the accuracy of route-distance estimates between first floor and second-floor rooms. In all conditions, the distance to first-floor rooms was underestimated.

DEA data from estimates of novel routes supported the hypothesis. Estimates of route-distance between rooms on the same floor were more accurate than estimates for rooms on different floors.

> H7: Azimuth estimates for origin-target pairs that are on different floors will be less accurate than for origin-target pairs that are on the same floor.

The AA data for known routes did not support the hypothesis. AA for targets on the second floor was more accurate than AA for targets on the first floor. There were no significant differences in azimuth accuracy for novel routes.

The AA data are consistent with the DEA data. Azimuth estimates for known routes on the first floor were greater than for known routes on the second floor. This is consistent with the underestimation of distances to first-floor rooms. That is, if the participants believed that the first-floor rooms were closer (as suggested by the underestimation of distance), the direction they would point would be farther from the starting azimuth thereby resulting in a positive AA score.

The figure below shows the relationship between estimated distance and estimated azimuth. If a room on the first floor is at location 1 then the azimuth is θ. If the participant believes the room is at location 1', the participant will underestimate the distance (which is what was found in this experiment). If they underestimate the distance, their azimuth accuracy score will be positive, i.e., θ' will be greater than θ. If one assumes that the azimuth estimate is based on their distance estimate, then the azimuth estimates for both floors are "accurate" in that they accurately reflect the position of room locations in the participants' cognitive maps of the VE.

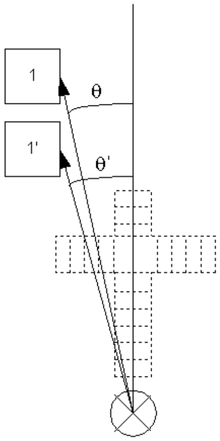


Figure 82. Effect of estimated distance on azimuth accuracy

> H8: Elevation estimates for origin-target pairs that are on different floors will be less accurate than for origin-target pairs that are on the same floor.

Not surprisingly, analysis of the known-route EA data supported this hypothesis. Elevation estimates were more accurate for first-floor rooms than for second-floor rooms. Participants overestimated the elevation of second-floor rooms. Given the mean EA for first-floor rooms was zero, the only conclusion that can be drawn from this result is that participants knew which floor a room was on. If they did not change the default elevation when they were pointing to first-floor rooms, then the EA for that starting-point-room pair was zero.

Analysis of the novel-route EA data found a similar pattern. Elevation estimates were more accurate for rooms on the same floor than for rooms on a different floor. When the rooms were on different floors, it did not matter if the participants were pointing from the first to the second floor or from the second floor to the first floor. In both cases, participants overestimated the elevation, i.e., they pointed above the target.

The overestimation of elevation when pointing toward the second floor is consistent with the underestimation of the distance from the starting-point to the rooms. If participants estimated elevation based on the estimated distance to a room and they underestimated the distance to the room, then the elevation estimate would be greater than the target estimate. In the figure below, boxes 1 and 2 represent the locations of rooms on the first and second floor, respectively, e.g., Broccoli and Peaches. Box 2’ represents the position of room 2 if participants believed that the rooms on each floor were vertically aligned. Box 1’ represents the position of room 1 based on the underestimation of the distance from the starting-point, ⊗

, to room 1. Box 2’’ represents the position of room 2 if the participants believed the rooms were vertically aligned and they underestimated the location of room 1. α is the target elevation when the participant points to room 2 from the starting-point. α’ is the estimated elevation based on the estimated position of room 2. As shown in the figure below, α’ is greater than α- which is what was found when participants pointed from the first to the second floor.

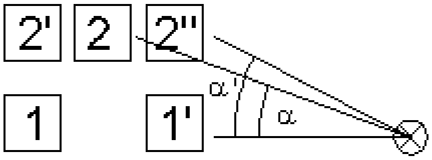


Figure 83**.** Effect of estimated distance on elevation accuracy when pointing toward rooms on the second floor.

> H9: When making a decision about a room location, the participant’s RT will be shorter when the prime and the target are on the same floor than when they are on different floors.

The results did not support the hypothesis. There was no difference in RT between the same-floor and different-floor pairs as a function of the elevation of the rooms in the pairs.

> H10: Navigation on routes whose origin and target are on the same floor will take less time than navigation on routes whose origin and target are on different floors.

> H11: The number of navigation errors on routes whose origin and target are on the same floor will be less than the number of navigation errors on routes whose origin and target are on different floors.

The POD data do not support hypothesis 10. POD for rooms on different floors was significantly less than POD for rooms on the same floor. This suggests that participants knew which floor the target room was on and that traveling to the starting-point provided an advantage in navigating between two rooms. If the rooms were on different floors, participants could formulate a navigation strategy by linking two pieces of route knowledge: (1) the route from the origin room to the starting-point, and (2) the route from the starting-point to the target room. Both routes were perfected during the learning trials. If the rooms were on the same floor, the participant had to formulate a novel route. Apparently, this was more difficult than linking two known routes.

The EED data do not support hypothesis 11. There were no differences in EED as a function of the elevation of the origin and target rooms.

Relationship to Previous Research. Only two other sets of researchers have investigated the effect of elevation on spatial memory. Garling, Book, Lindberg, and Arce (1990) had participants choose which of two locations was higher or lower (the task changed across trials). RT, when making the decision, was affected by the difference in elevation between the two locations. RT was greater when the difference in elevation was smaller. The absence of an effect of distance between the two locations led them to conclude that elevation information can be retrieved from memory separately from distance information. In other words, even if elevation and distance are integrated, for certain tasks, they can be separated so that one does not affect the other.

In the present study, it does not appear that elevation and distance can be separated. Unfortunately, the difference between the effects found for novel routes and known routes makes interpretation difficult. For known routes, the effect of elevation on the route-distance estimates suggests that participants added distance to routes going to the second floor to account for the change in elevation. This would make sense if the rooms on each floor were vertically-aligned. For example, if the rooms were vertically-aligned (as they are in most multi-story buildings) and participants estimated that the distance to Potatoes was X, then the distance to Oranges should be X + c, where c is a constant distance that accounts for the distance traveled while going up the stairs.

For novel routes, the effect is the opposite of that for known routes. Route distances between floors were underestimated in comparison to routes on the same floor. There is no apparent reason for this pattern of results. There is no indication that participants were confused about the floor on which a room was located. Examination of the same room-room pairs in the pointing task shows that participants knew that the rooms were on different floors. One would have to assume that participants subtracted distance for between-floor routes or added distance to same-floor routes. Neither explanation makes sense.

Montello and Pick (1993) had participants learn two routes, separately, in and around several buildings. One route was below the other and below ground. Each route contained four landmarks that were vertically aligned between routes. After learning the routes, participants went to each landmark and pointed toward the other landmarks. Azimuth was recorded. Montello and Pick found that azimuth error was greater when pointing toward landmarks on the other floor.

A direct comparison between the AA data from this experiment and the pointing accuracy of Montello and Pick's participants is difficult. In their experiment, participants pointed toward locations that were on a known route. However, the known route was not the shortest route between the landmarks. When pointing toward a landmark on the same floor, it is unclear whether participants used the known route when estimating azimuth or whether they based their direction estimates on novel routes they knew existed but had not been traveled. When pointing toward a landmark on a different floor, one can assume that the participants relied on survey knowledge since they had not learned a route between landmarks on different floors.

The magnitude of the azimuth errors, found by Montello and Pick, suggest that participants did not rely on the known route when pointing toward the landmarks on either floor. Unlike Montello and Pick, the difference in this experiment was not significant. However, Montello and Pick measured absolute azimuth error. Converting the data from this experiment to absolute values, shows that participant azimuth accuracy for novel routes is comparable between the two experiments.

Distance. Rooms in the VE were placed at one of three distances from the starting-point. Memory for known routes was assessed across all three distances. Room-room pairs, used to assess memory for novel routes, used two distances. In the arbitrary units of the VE, the three distances from the starting-point were 50, 150, and 250. The two distances separating room-room pairs were 100 and 200. This section discusses the hypotheses involving Distance and the support provided for the hypotheses by this research.

> H12: Route-distance estimates for origin-target pairs that are farther apart will be less accurate than for origin-target pairs that are closer together.

The DEA data for known routes did not support the hypothesis. On the first floor, DEA for the longest and middle-distance routes were more accurate than DEA for the shortest routes. Route-distance did not affect DEA for second-floor rooms. The effect of distance was also affected by the number of turns on a route. When there were no turns on the route, DEA was more accurate for the longest routes in comparison to the shortest routes. When there were 2 turns on the route, route-distance had no effect on DEA.

Route-distance had no effect on DEA for novel routes.

> H13: Azimuth estimates for origin-target pairs that are farther apart will be less accurate than for origin-target pairs that are closer together.

The known-route data support the hypothesis. Azimuth estimates for rooms at the longest or middle distance were less accurate than for rooms at the shortest distance. The novel-route data do not support the hypothesis. There were no differences in AA as a function of distance.

> H14: Elevation estimates for origin-target pairs that are farther apart will be less accurate than for origin-target pairs that are closer together.

The analysis of known-route EA data supported the hypothesis. When participants pointed to second-floor rooms, elevation accuracy was best for rooms separated by the shortest distance and worst for rooms separated by the longest distance.

The novel-route EA analysis partially supported the hypothesis. When participant pointed toward a room on the other floor and the origin and target were separated by two turns, elevation accuracy for rooms at the short distance was better than for rooms at the long distance.

> H15: When making a decision about a room location, the participant's RT will be shorter when the prime and the target are closer together than when they are farther apart.

The results did not support the hypothesis. RT was not affected by the distance between the origin and target.

> H16: Navigation on routes whose origin and target are farther apart will take more time than navigation on routes whose origin and target are closer together.
>
> H17: The number of navigation errors on routes whose origin and target are farther apart will be greater than the number of navigation errors on routes whose origin and target are closer together.

The distance between the origin and target rooms had no effect on POD or EED. These results do not support the hypotheses.

Relationship to Previous Research. Byrne (1979) found that route distance affected route distance estimates. Shorter routes were overestimated in comparison to longer routes. Ruddle, Payne, and Jones (1997) found no effect of distance. In their experiment, participants estimated route distances between points in a VE. Their participants showed no consistent tendency to underestimate or overestimate route distances. Lloyd and Heivly (1987) found that participants consistently overestimated distances between landmarks and that the actual distance between the landmarks had no effect on the accuracy of the estimates.

In this experiment, the effect of route distance depended on route type. For known routes, participants underestimated shorter distances in comparison to longer distances. For novel routes, the opposite was true; participants overestimated shorter distances in comparison to longer distances. Given the equivocal results of this and other research, more work is needed to understand the effect of distance on distance estimates. The use of virtual environments may affect the accuracy of distance estimates as may the duration of exposure, and type of task used to learn the environment. The participants in this study and in Ruddle, Payne and Jones (1997) only experienced the environment for a few hours. In both experiments, participants were given specific navigation tasks which were intended to teach the participant the layout of the environment. Other than learning the environment, the participants had no other reason to be in the VE. Participants in Byrne’s and Lloyd and Heivly’s studies were residents of the area being studied. Their exposure to the environment ranged from months to years. Their navigation of the environment probably had more than one purpose. In most cases, they were probably trying to accomplish something other than learning the environment, e.g., visit a friend or go to the store.

Cornell, Heth, & Alberts (1994) found that pointing accuracy declined as the distance from the origin to the target increased. Similar results were found in this experiment. For known routes, AA was more accurate for shorter routes than for longer routes. For novel routes, the distance between the origin and target had no effect on AA. At both distances, participants pointed closer to the origin than the actual azimuth. No other research has investigated EA as it is affected by distance. However, one could assume that the same information underlying azimuth accuracy also underlies elevation accuracy. The pattern of results for EA was similar to that of AA, suggesting that distance has the same effect on elevation and azimuth estimates. This also suggests that the pointing task involves both elevation and azimuth and that they are not separable into component tasks.

Turns. The routes between the starting-point and rooms or between room-room pairs contained either zero or two turns. The number of turns on a route was expected to affect the accuracy of memory for the route and the relative position of the beginning and end of the route. It was expected that memory for routes with two turns would be less accurate. Route-distance estimates would be less accurate because the participant would estimate the route by estimating each leg of the route. Routes with two turns have three legs. Routes with zero turns have one leg. Estimates of three legs would be more prone to error than estimates of one leg. Direction estimates would be less accurate because the participant would have to perform mental trigonometry to derive the straight line connecting the end points of the route. This section discusses the hypotheses involving Turns and the support for the hypotheses provided by this research.

> H18: Route-distance estimates for origin-target pairs that are separated by routes with turns will be less accurate than for origin-target pairs separated by routes without turns.

The known-route DEA data partially supported the hypothesis. When estimating route-distances for known routes, participants were more accurate when estimating distance for routes with 0 turns than for routes with 2 turns. However, when comparing DEA for 0-turn and 2-turn routes at each distance, this difference was significant at the longest distance only. The difference in DEA, between 0-turn and 2-turn routes, was significant for routes on the first floor only.

The novel-route DEA data did not support the hypothesis. The number of turns on a route did not affect DEA.

> H19: Azimuth estimates for origin-target pairs that are separated by routes with turns will be less accurate than for origin-target pairs separated by routes without turns.

The AA data for known routes did not support the hypothesis. At the middle distance, azimuth accuracy was better for routes separated by 2 turns than for routes separated by 0 turns. There was no difference in azimuth accuracy at the shortest and longest distances.

The AA data for novel routes did not support the hypothesis. At the longer distance, azimuth accuracy was better for routes separated by 2 turns than for routes separated by 0 turns. There was no difference in azimuth accuracy at the shorter distance.

> H20: Elevation estimates for origin-target pairs that are separated by routes with turns will be less accurate than for origin-target pairs separated by routes without turns.

The results of the known-route EA analysis did not support the hypothesis. The number of turns on the route separating the room from the starting-point had no effect on elevation accuracy.

In contrast, the analysis of the novel-route EA data partially supported the hypothesis. EA for rooms separated by 0 turns was more accurate than for rooms separated by 2 turns. This effect was significant only for rooms separated by the shorter distance. At the long distance, there was no difference in the accuracy of elevation estimates between 0-turn and 2-turn routes.

> H21: When making a decision about a room location, the participant's RT will be shorter when the prime and the target are separated by routes with no turns than when they are separated by routes with turns.

The results did not support the hypothesis. The number of turns on the route between the prime and target rooms did not affect RT.

> H22: Navigation on routes with turns will take longer than navigation on routes without turns.
>
> H23: There will be more errors during navigation on routes with turns than on routes without turns.

The POD data partially supported the hypotheses. When the origin and target rooms were on the same floor, POD was significantly greater on routes with 2 turns than on routes with 0 turns.

The EED data did not support the hypotheses. There were no differences in EED as a result of the number of turns along the route between the origin and target rooms.

Relationship to Previous Research. Thorndyke and Hayes-Roth (1982) propose that the number of turns along a route will affect the accuracy of route distance estimates and the estimate of the direction from the route origin and end. When a route has turns, the participant must estimate the distance of each leg and the angle of intersecting legs. Every leg and every turn presents the possibility of inaccurate estimates of distance or direction. As the number of turns increase, the accuracy of the route distance estimate and the direction estimate decrease.

The data from the distance-estimation task in this experiment only partially support Thorndyke and Hayes-Roth. When estimating route distances, the number of turns on a route only affected estimates for known routes on the first floor. The number of turns on a route had no effect on AA and a small effect on EA.

The failure to find an effect of Turns may be the result of the regularity of the VE. One common source of errors in distance and direction estimates is the result of people's tendency to "square-off" turns, i.e., people believe that routes intersect at a 90^0 angle (Byrne, 1979). Since all of the turns in the VE were 90^0 turns, one possible source of error has been eliminated. The "right-angle" heuristic, that usually causes errors, matches the physical characteristics of the VE. The distances between intersections was also constant which may have made estimating route legs easier than if the distances had been irregular (as they would be in the real-world).

<u>Route and Survey Knowledge</u>. The differences in performance between the starting-point and room-room pairs suggest that memory for route knowledge is different from memory for survey knowledge. Only one effect was the same for both known and novel routes. There was a significant Distance effect on elevation estimates. For both novel and known routes, participants overestimated elevation for rooms that were farther away in comparison to rooms that were closer. The Distance x Floor/Elevation interaction showed that this effect only existed for rooms that were on the second floor (known routes) or a

different floor (novel routes). Although there was a significant effect of Floor (known routes) and Elevation (novel routes) on distance estimates, the direction of the effect was the opposite for known and novel routes. When estimating novel-route distances, participants underestimated the distance to rooms on the other floor. Their estimates of distances to rooms on the same floor were almost perfect. In comparison, when estimating known route-distances, participants underestimated the distance to rooms on the first (same) floor. Their estimates of routes to the second (other) floor were almost perfect.

In all other cases, the differences were found in either known or novel routes but not in both. One assumption might be that performance on the novel-route (room-room) pairs was uniformly inferior to the performance on the known-route pairs. This was not the case. In most instances the participants' memory was accurate for both types of routes. The failure to find consistent differences may be the result of the type or scale of the environment. While the VE can be considered a large-scale environment, differences in route and survey knowledge may only become consistent, large, and influential on memory when the distances involved are greater than those in this experiment.

Conclusions

Unlike previous research which showed that non-spatial and spatial information can be integrated, the results of this experiment suggest that integration of non-spatial information into a cognitive map requires highly salient non-spatial information. Semantic group membership affected only the azimuth accuracy in the distance-estimation task. The interaction of room elevation and semantic group was equivocal. It is unlikely that semantic group membership affected azimuth accuracy without affecting performance on any of the other tasks. In comparison to the consistent pattern of results, as influenced by the spatial characteristics of the VE, it appears that non-spatial information had little influence on memory of the VE.

In this research, the non-spatial information was insufficiently salient, in comparison to that of the spatial information, to affect memory for the environment. For non-spatial information to affect memory for the environment, it must be integrated into the environment in a way that affects navigation in the environment or understanding of the structure of the environment. Most likely, the overwhelmingly spatial nature of the navigation tasks in the learning trials made the semantic group manipulation irrelevant during the acquisition of route knowledge. The failure of participants to realize that semantic group was associated with room location prevented semantic group from affecting memory for the environment.

The strongest evidence for the lack of integration comes from the failure of the room-location-decision task to reveal any differences in RT as a result of differences in semantic group membership between the prime and target. Another casualty of the failure of the room-location-decision task is the ability to develop substantial evidence for a hierarchical knowledge structure. One would have expected that the physical relationship between the prime and target would also have affected RT. According to the theory underlying the decision task, the appearance of the prime room activates the room's representation in memory. As the activation spreads, the contents of closely-associated memory are also activated. RT is supposed to be a function of the proximity of the prime and the target in memory. The more closely the prime and the target are associated, the more quickly the target is activated after the prime is activated and the faster the participant responds, i.e., RT is shorter. In a hierarchical structure, rooms within the same hierarchical groups are associated. If the prime and target are from the same hierarchical group, RT should be shorter than when they are in different groups. The absence of any differences in RT suggests that either (a) the knowledge structure containing memory for the VE is not hierarchical, or (b) the knowledge structure is hierarchical but the RT does not reflect the speed at which the memory for room location is activated. As discussed earlier, it is likely that the participants' RT is not indicative of the speed at which memory was activated.

While non-spatial information was not integrated into the mental representation of the VE, there is some evidence that a cohesive structure was formed during the learning trials and affected performance during the post-learning tasks. The results from the learning trials suggest that participants learned the location of rooms based on their distance from the starting-point and whether there were turns on the route to the rooms. After dividing rooms into smaller groups, based on distance and turns, participants learned each room's floor.

It appears that participants first separated rooms into three groups based on distance and turns. One group was comprised of rooms close to the starting-point. The other group contained rooms far away from the starting-point. The third group contained rooms that were along the edges of the VE, i.e., getting to these rooms required turning off of the main hallway. Evidence for this division of rooms is found in the difficulty of learning the location of rooms at the middle distance. Participants anchored their first three groups to the physical characteristics of the VE, i.e. the stairs and the outer walls. Rooms in the middle could not be anchored to any differentiating attribute and their relationship to the other rooms and the starting-point was difficult to establish.

Once participants learned that rooms were in one of three locations (1) near the stairs, (2) at the far end of the main hallway from the stairs, or (3) along one of the side walls, they began learning the rooms' floor. In other words, elevation was the last part of the knowledge that was learned. Evidence for this comes from the constant ratio of the number of trips in which EED was greater than 0 to the number of trips in which POD was greater than 0 (shown in Figure 83) and the constant magnitude of EED for those trips in which EED was greater than 0 (shown in Figure 82). If participants learned the rooms' floor first, EED would have been near zero before the fifth trial. Participants would have known which floor they should search but not have known where to search on that floor. If this were the case, POD would remain high and EED would be close to zero.

Even though elevation was the last spatial component of room location learned by the participants, there is evidence that elevation strongly influenced their memory for the VE. Estimates of known-route-distances were more accurate for routes leading to the second floor than for first-floor routes. First-floor routes were underestimated in comparison to second-floor routes. The most likely explanation of this result is that participants underestimated the distance to the rooms on the first floor and assumed that the rooms on the two floors were vertically aligned. When they estimated the distance to the second-floor rooms, they added a constant distance to account for the change in elevation, i.e., going up the stairs, this change in elevation compensated for the underestimation of the distance to the first-floor rooms. For example, if a participant was asked to estimate the distance to Oranges, they would first estimate the distance to Potatoes and then add the constant distance to account for the stairs.

The direction-estimation task shows a pattern of results consistent with the results of the route-distance-estimation task. When pointing toward first-floor rooms, participants pointed farther from the mid-line (0^0) than the target azimuth. In other words, if the room was to the right of the mid-line, they pointed to the right of the target azimuth. If the room was to the left of the mid-line, they pointed to the left of the target azimuth. Although these estimates were inaccurate, in comparison to second-floor rooms, they were consistent with the participants' estimates of the distance to the first-floor rooms. If the rooms were at the distances estimated by the participants, the azimuth estimates would be accurate.

More support for a consistent mental representation of the VE comes from the accuracy of the elevation estimates. As expected, participants knew which floor a room was on when they were pointing toward it. In those cases where participants pointed from the first floor to the second floor, participants pointed above the target elevation. This is consistent with the underestimation of the distance from the starting-point to the rooms and the assumption that rooms on the two floors are vertically aligned.

Finally, it was apparent that navigation depends on different knowledge than do the route-distance-estimation and direction-estimation tasks. In comparison to the distortions of distance and direction found in the estimation tasks, performance on the final navigation task was near perfect.

Critique of this Research

While running the experiment and analyzing the results, it became apparent that there were improvements that could be made to the methodology used in this study. This section discusses changes to the methodology that could improve the research.

Number of Independent Variables

The difficulty in designing the VE and the complexity of the analysis suggest that reducing the number of independent variables would (a) reduce the amount of time needed to learn the environment, (b) reduce the complexity of the analysis, and (c) make interpretation of the results more straight forward. Elevation and semantic group membership should be separated and examined in separate studies. One experiment could manipulate distance, turns, and elevation- all physical features. The other experiment could control these physical features and manipulate non-spatial characteristics.

Nature of Independent Variables

The external validity of these results is limited by the uniqueness of the room names. It is not clear whether room names drawn from other semantic groups would produce similar results. It is likely that some of the performance in the learning trials arose from interactions among room names and their locations. For example, several participants repeatedly confused Plums and Peas even though their locations were as far apart as possible. The confusion may be based on the similarity of the first phoneme in the room name. One way to reduce this effect would be to randomly assign room names to rooms for each participant.

One problem with the introduction of changes in elevation is the confounding of straight-line distance and route-distance. Given the difficulties of designing a VE that fully-crossed the four IVs used in this experiment, there was no way to control straight-line distance between rooms. Future research should investigate whether straight-line distance interacts with route-distance in memory for the VE. For example, if two rooms are vertically-aligned but the route-distance between them is large, will they be closely associated in memory or more strongly associated with other rooms on the same floor?

Dependent Variables

Navigation on novel routes did not provide any meaningful information about the nature of memory for the VE. As expected, performance was near perfect and unrelated to performance on the other dependent measures. Without modification to the VE, it is unlikely that this will change. One way to increase the difficulty of the task would be to increase the number of routes between rooms. By adding several sets of stairs, the novel-route navigation task becomes more difficult. The shortest route between two rooms may not pass through the starting point. Participants must remember where the origin and target rooms are in relation to stairs, hallways, and each other before choosing the shortest route.

The room-location-decision task found no significant effects. As discussed earlier, this may have been caused by the instructions given to the participants. In the future, these instructions should emphasize that the speed of response is of paramount importance as long as the participant’s response speed does not compromise their accuracy to the extent that the percentage of incorrect responses makes the data of questionable use.

Future Research

Cognitive maps arise from complex environments, existing environmental knowledge, and navigation goals. In this experiment, every participant's navigational goals were the same, i.e., the goals were defined by the structure of the learning tasks. All participants' existing environmental knowledge was identical at the beginning of the experiment. Their exposure to the environment during the experiment was controlled. This suggests, not surprisingly, that there are individual differences in people's ability to form coherent or accurate representations of environments. It would be useful to understand the basis of those differences. Future research could address the nature of individual differences in the development of cognitive maps and the structure of this knowledge as it pertains to people's memory for the environment and their ability to navigate in the environment.

One source of individual differences could be prior navigational experience in the real-world or in other VEs. People probably base their navigational strategies in the VE on their navigational strategies developed in the real-world. These strategies are likely to rely on spatial and non-spatial information. The VE in this experiment was designed to maximize control over its spatial and non-spatial characteristics. In effect, many of the spatial characteristics as they pertained to the routes participants had to learn, could be objectively defined. This was intended to minimize the potential effect of unplanned influences by environmental characteristics which were included in the environment to increase the feeling of presence (Draper, Kaber, & Usher, 1998) in the VE. Yet people select the salient aspects of their environments and encode the same environment differently (Golledge, 1991c). It would be useful to expose participants navigational strategies to identify the salient environmental characteristics of the VE and determine their effect on performance. For example, the participants could provide verbal reports concurrent with learning the VE.

Since most navigation involves both spatial and non-spatial information, future research should investigate methods of creating semantic groups in a VE and measuring the effects of the groups. The results of this research would suggest that spatial memory for a VE is not subject to some of the distortions commonly found in spatial memory for the real-world. Yet the VE is obviously lacking in the richness, detail and nuance of the real-world. A VE can mimic the spatial characteristics of the real-world, e.g., distance, route complexity, and elevation, but it is more difficult to recreate the non-spatial components. It is the non-spatial components of navigation that make each trip unique. The lack of integration of non-spatial knowledge may also be the result of its relative unimportance to the learning task in comparison to the distance to a room and the number of turns on the route to a room. Modification of the procedure could make the semantic group membership of a room more salient, thereby increasing the effect of non-spatial information on environmental knowledge.

VEs and Spatial Cognition

This research shows that VEs can be used to study spatial cognition. What is not well understood is whether spatial cognition in a VE is the same as spatial cognition in the real-world. It appears that participants developed a consistent and accurate representation of the VE. They acquired this knowledge in the same way most people learn about any environment- by navigating through it. More research, similar to the research reported here, is necessary to determine if the patterns of results are similar when spatial knowledge is acquired in a VE as compared to when it is acquired in the real-world.

The small variability in performance across participants suggests that there are aspects of real-world environments or navigation in real-world environments that are not captured in the VE. One would expect greater variability across all measures if this task were performed in a real-world setting. One explanation is that the level of detail that is possible in a VE is not adequate to simulate all influences on navigation in the real-world. Because limited computing resources are available to build and run a VE, their complexity is often intentionally minimized to avoid lags in their responses to people's movements. It is not clear if making a VE richer in detail would hinder or facilitate navigation and the development of an accurate cognitive map.

Previous research has shown that VEs have been used to train people for navigation in the real-world (Bliss, 1997). Results of this research support the assumption that a VE can be a stand-in for a real-world environment if the trainee is expected to learn how to navigate in the environment. Existing research and development programs (Bailey & Witmer, 1994; Satalich, 1995; Aginsky, Harris, Rensink, & Beusmans, 1996) indicate that others have found similar success in training people to navigate through VEs.

One result from this experiment does point to a potential problem with using VEs as a training device. In the navigation of novel routes, participants had difficulty when asked to travel between two rooms on the same floor that were separated by a route with turns. As explained previously, the absence of this effect for routes between floors can be explained by participants' reliance on route knowledge in the between-floor routes. Their difficulty with the same-floor routes indicates that developing survey knowledge, even in a simple environment like the one used in this experiment, may not be easy.

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Appendix A

Informed Consent Form

North Carolina State University
INFORMED CONSENT FORM

Title: Cognitive Mapping In Virtual Environments

Principal Investigator: Todd Barlow **Faculty Sponsor:** Sharolyn Converse, Ph.D.

You are invited to participate in a research study. The purpose of this study is to investigate how people learn their way around virtual environments.

INFORMATION

1. Participants will be asked to navigate through a virtual environment. After learning their way around the environment, they will be asked to demonstrate their knowledge for the environment.
2. This experiment lasts approximately 2 hours.

RISKS

There is no known risk associated with participation in this experiment.

BENEFITS

This study contributes to the understanding of the development and structure of knowledge of a virtual environment arising from direct experience with the virtual environment.

CONFIDENTIALITY

The information in the study records will be kept strictly confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwise. No reference will be made in oral or written reports which could link you to the study. Data will be stored and referenced by the participant’s number rather than by the participant’s name.

COMPENSATION

For participating in this study you will receive 4 research participation credits. Ask your instructor about other ways to earn the same amount of credit . If you withdraw from the study prior to its completion, you will receive 1 credit for each ½ hour, of participation.

CONTACT

If you have questions at any time about the study or the procedures, you may contact the researcher, Todd Barlow at 481-2711, 481-0565, or tbarlow@montereytechnologies.com. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact the Dr. Gary A. Mirka, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7906, NCSU Campus.

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature____ **Date** _________

Investigator's signature_______________________________________ **Date** _________

Participant Instructions

NOTE: Experimenter actions appear in italics. Experimenter dialogue appears in plain text.

Introductory Instructions

Read these before doing anything else.

Hello. Thank you for coming. Today you will be participating in a research that investigates how people learn about virtual environments. For the next two hours, you will learn the environment and perform a series of tasks that will tell us about your knowledge of the environment.

Before we begin, you need to sign an informed consent form. This form says that you have volunteered to participate in this research and that you may withdraw from the research at any time without penalty.

Give the participant the form.

If you don't have any questions, please sign and date the form.

Take the form after they sign it and put it in the participant's folder.

Thank you.

VE Familiarization

As I said, this research studies how people learn about virtual environments. I will ask you to learn the layout of a virtual environment and then perform some tasks that show what you have learned about the environment.

First, I'm going to show you some things about the virtual environment. I'll show you how to move around and what you will see in the environment.

Turn on the TV and make sure the practice environment is loaded. Begin recording with the VCR. Seat the participant next to you so you can both see the joystick and the VE. Place the joystick in front of you on the table.

What you see on the TV is similar to the virtual warehouse. The colors and textures are identical to what you will see in the environment we will use for the study. Just as in a real warehouse, there are halls, doors, and stairs that allow you to move around.

You will use the joystick to move yourself through the environment. You can move forward, backward, and turn. *(Demonstrate these movements)*

To move forward, push the joystick forward *(demonstrate).*

To move backward, pull the joystick backward *(demonstrate).* It does not take much movement or force to move the joystick and the speed and force you use does not affect how fast you move in the environment- so please don't abuse the joystick.

To turn, turn this knob to the right or left *(demonstrate).* Notice the cross in the center of the screen? That is the direction your virtual body is pointing. You can use that to help you direct your movements.

You can also combine any of the joystick and knob movements. For example, I can move forward while turning the knob *(demonstrate).*

Any questions? *(Answer their questions.)*

See that red line on the floor, I'm going to follow it. Watch what I do while I move through the environment. When I'm done, you'll get to practice.

Follow the practice route. When you are done following the practice route, place the joystick in front of the participant. Seat them in front of the TV.

Now you are going to practice moving around in the virtual environment.

Move forward by pushing the joystick forward.
Move backward by pulling the joystick backward.
If they are jerking on the joystick and using too much force, remind them that the speed and force they use does not affect the speed at which they move. They should be gentle with the joystick.
Turn around by turning this knob.

Now let's practice moving through the environment. Follow the red line on the floor.

Now turn around and go the other direction.

The participant should follow the practice path twice in both directions. After they finish the four practice trials, show them the door.

This is a door. You will be looking for similar doors in the virtual environment. The only difference is that a room number will appear in the yellow box and a room name will appear in the maroon rectangle. When I ask you to find a room, you will search for the room with the room name and number. When you find it, I want you to run into the door and press either of these buttons.

Demonstrate running into the door and pressing one of the Jump buttons, then move back from the door.

Now you practice. You don't have to be precise. Simply run into it at any angle and press one of the buttons.

Let them practice running into the door and jumping.

Learning Trials

Load the real environment.

Now that you know how to move around in the environment, you'll start learning more about it.

The virtual environment we will use is a virtual warehouse. This warehouse stores vegetables and fruits. Each fruit or vegetable is stored in its own room and the room is name is the name of the fruit or vegetable. For example, there is a room named "Asparagus" in which the asparagus is kept. One of your tasks is to learn where these rooms are, in the warehouse, and how to get from one room to another.

Each of these rooms is also numbered. This should help you find your way around the warehouse.

You will learn the names and locations of the rooms by traveling from this location, at the bottom of the stairs, to a room and back again. Your goal is to find the shortest route from this location to the room and back again.

At first, I will give you a room name and number. The room numbers should help you find the rooms initially, but you should not rely on the numbers alone. You should try to remember the room locations without the room numbers. After finding each room twice, with the room numbers, I'll ask you to find it again, but I won't give you the room number.

When you find the room, run into the door and press one of these buttons- just like you did a few minutes ago. After that, go back to the starting point at the bottom of the stairs (where you are standing now) and run into the wall at the bottom of the stairs and press one of these buttons. Any questions?

Answer their questions. Give the participant the first name and number. Use the list of room names assigned to this subject.

@@@
Here is the room name(and number). Please find the room.

Start timing. Stop timing when they reach the room and press the button. Write the time on the data sheet.

Now return to the bottom of the stairs.

Start timing. Stop timing when they reach the bottom of the stairs and press the button. Write the time on the data sheet.

***

Shortest route to room?	**Shortest route to stairs?**	**Instruction**
No	No	A
Yes	No	B
No	Yes	C
Yes	Yes	D

A. You were able to find the room and return to the stairs but you did not find the shortest route. The next time I give you this room name, please try to find the shortest route.

Load the map. Give the participant the next room name (and number). Return to @@@

B. You found the shortest route to the room but you didn't travel back to the stairs on the shortest route. The next time I give you this room name, please try to find the shortest route to the room and back to the stairs.

Load the map. Give the participant the next room name (and number). Return to @@@

C. You were able to find the room and return to the stairs but you did not find the shortest route to the room. The next time I give you this room name, please try to find the shortest route to the room.

Load the map. Give the participant the next room name (and number). Return to @@@

D. You found the shortest route to the room and back again. The next time I give you this room name, please try to follow the same route.

Load the map. Give the participant the next room name (and number). Return to @@@

Repeat this sequence twice for each route using the room names and numbers. Repeat this sequence four times for each route using the room name only.

After the participant completes four trials, without the room number, for each room, stop the video tape.

Route Distance Estimation

Load the map.

Now I'm going to ask you to estimate route distances between rooms. Route distance is the distance you would travel between the two rooms. If the route between two rooms is a straight line, route distance is the same as straight line distance. Otherwise, route distance is different from straight line distance. Any questions so far?

Answer their questions.

I'm going to show you a distance that I want you to use as a standard. This distance has a value of 100. After I show you this distance, I'll ask you to estimate the distance between two rooms. You will use the distance I show you as your standard. If the route distance between two rooms is twice the standard, then you would write down 200. If the route distance between the two rooms is ½ the standard, then you would write down 50. Any questions?

Answer their questions.

Here is the standard distance. The distance from the stairs to the red tile is equal to 100.

Show them the distance. Travel to the end of the route.

OK? Here it is again.

Turn around and travel back again. Turn off the TV. Start route distance estimation program.

You will be shown two location names. Enter your estimate of the distance between the two locations. After you write down your estimate, press Enter and continue with the next pair of names.

Stop when you the locations are Stop and Stop.

Direction and Straight Line Distance Estimation

Turn on the TV. Load the pointing/straight line map.

Now I'm going to ask you to estimate direction between rooms. I will ask you to imagine you are at one room and ask you to point, using the joystick, to another room.

Any questions?

To point to another room, turn this knob until the crosshair is pointing in the direction of the room. When it is pointing in the right direction, take your hand away from the knob. If the two rooms are not on the same floor, you can point up or down by moving this switch.

Show them how to move the switch.

Any questions about pointing the crosshair.

Answer their questions.

Reset the crosshair.

Here is the first pair of rooms. Imagine standing in front of the door of the first room. Point the crosshair toward the second room.

When the participant indicates they have finished moving the crosshair, press A and record the azimuth and elevation angles.

Reset the crosshair and repeat the procedure until the participant finishes with all of the pairs in the packet.

Room Location Decision

Seat the participant in front of the monitor and keyboard.

In this task you will decide whether a room was on the first or second floor. To begin, you press the space bar and an asterisk appears very briefly. Look at the asterisk because this is where the room names will appear. The asterisk will be replaced by a room name. This room name will remain on the screen for a very short time. Read the name of the room to yourself. This name will be followed by the name of another room. When you see this room name, you must decide whether it was on the first or second floor. If it was on the first floor, press the F key. If it was on the second floor, press the J key. Press the space bar again when you are ready for the next trial. Any questions?

First we'll try some practice trials.

Make sure the pointing fingers of their left and right hands are on the F and J keys.

Press the space bar when you are ready to begin.

Wait until they finish the practice trials.

Any questions?

Answer their questions.

Give the participant a 30 second break between each block of trials.

Navigation Test

Turn on the TV. Start recording with the VCR.

Now I'll ask you to travel from one room to another. You will start facing the door of one room and try to find the other room as quickly as possible. When you get to the room, take your hands off the joystick. Any questions?

Answer their questions. Give them the first pair of rooms and load the appropriate map.

You are at <room name>. Find <room name> as quickly as possible.

Start timing. Stop timing when they reach the room and press the button. Write the time on the data sheet. Remove the room name and number.

Load the next map and give them the next pair of names.

Interpretation of Box Plots

Box plots are pictorial representations of the distribution of values of a variable. The central line in each box marks the median value. The edges of the box mark the first and third quartiles. The "whiskers" on the box plot are drawn from the quartiles to the farthest observation not farther than 1.5 times the distance between the quartiles. Observations whose values are greater than 1.5 times the distance between the quartiles are shown as individual observation markers. These observations are usually considered outliers. The diamond shows the mean and standard deviation of the distribution. The central line is the mean. The points above and below the line are one standard deviation above and below the mean, respectively. The figure below shows a box plot for a normally distributed variable, X.

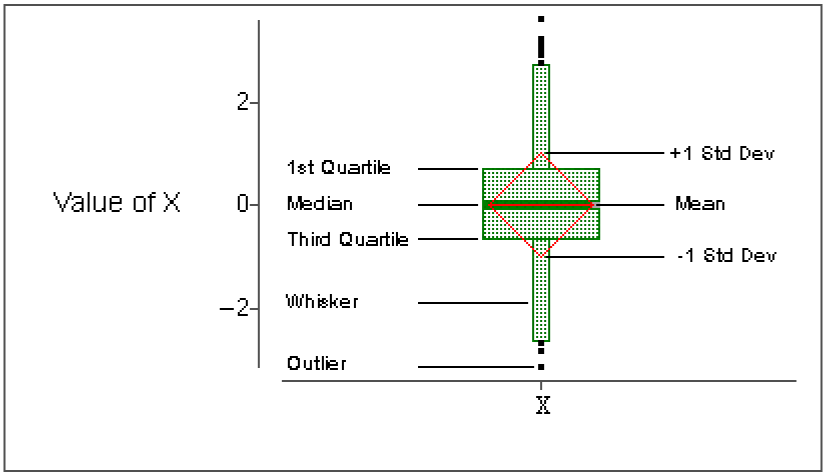

Figure 84. Box plot

Tour of the Virtual Environment

An AVI file, showing a part of the first floor of the VE, can be viewed by selecting this link. An AVI file, showing a part of the second floor of the VE, can be viewed by selecting this link.