Spatial Perception in Virtual Environments: Evaluating an Architectural Application.

by
DANIEL HENRY

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PREFACE

Over the last several years, professionals from many different fields have come to the Human Interface Technology Laboratory (H.I.T.L) to discover and learn about virtual environments. In general, they are impressed by their experiences and express the tremendous potential the tool has in their respective fields. But the potentials are always projected far in the future, and the tool remains just a concept. This is justifiable because the quality of the visual experience is so much less than what people are used to seeing; high definition television, breathtaking special cinematographic effects and photorealistic computer renderings. Instead, the models in virtual environments are very simple looking; they are made of small spaces, filled with simple or abstract looking objects of little color distinctions as seen through displays of noticeably low resolution and at an update rate which leaves much to be desired.

Clearly, for most applications, the requirements of precision have not been met yet with virtual interfaces as they exist today. However, there are a few domains where the relatively low level of the technology could be perfectly appropriate. In general, these are applications which require that the information be presented in symbolic or representational form. Having studied architecture, I knew that there are moments during the early part of the design process when conceptual decisions are made which require precisely the simple and representative nature available in existing virtual environments.

This was a marvelous discovery for me because I had found a viable use for virtual environments which could be immediately beneficial to architecture, my shared area of interest. It would be further beneficial to architecture in that the virtual interface equipment I would be evaluating at the H.I.T.L. happens to be relatively less expensive and more practical than other configurations such as the "Walkthrough" at the University of North Carolina. The set-up at the H.I.T.L. could be easily introduced into architectural firms because it takes up very little physical room (150 square feet) and it does not require expensive and space taking hardware devices (such as the treadmill device for simulating walking).

Now that the potential for using virtual environments in this architectural application is clear, it becomes important to verify that this tool succeeds in accurately representing space as intended. The purpose of this study is to verify that the perception of spaces is the same, in both simulated and real environment. It is hoped that the findings of this study will guide and accelerate the process by which the technology makes its way into the field of architecture.

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I want to thank the Henry Art Gallery and their entire staff for their input during the process and for their generosity in letting me use their gallery spaces for this study. Similarly, I would like to thank the professional designers, the graduate students in architecture and the architecture faculty for their participation. Their involvement in the development of virtual interfaces is an important condition for making sure that the tool will be beneficial to their professional community.

I would also like to thank all of the H.I.T.Lab staff and students and the numerous architecture students and faculty who were so generous in their support at various stages of this study.

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INTRODUCTION

What makes virtual environments distinct from all other human-computer interfaces is that the human being has the illusion of being completely surrounded by spatial information. In these computer generated environments, the human being becomes a participant. The illusion is sufficiently compelling for participants to develop a sense of actually being present within the synthesized space. It makes the interpretation of the information and interaction with the environment particularly easy because it requires the same spatial perceptual skills as does the interpretation of real environments.

While there are many potential applications which could benefit from being presented in these environments, the simulation of architectural spaces is perhaps the most obvious one. Is satisfies a real need in the architectural community, that improving the communication between the designer who relies on architectural representations, and the client whose best understanding of the design occurs only when being physically present within the space.

Designers' existing forms of spatial representation require intellectual abstraction and offer only limited views. Perspective renderings are fixed and pre-determine our choice of views. Models are three dimensional but they cannot be entered. Computer animations are dynamic but, as the path is pre-determined, they also restrict our views. In virtual environments, participants are free to look, move and see most closely to the way they would in the real environment. Virtual interfaces become the ultimate perspective drawing, the ultimate model, the ultimate computer animation for describing an architecture project.

But while simulations can be very effective in representing spaces, their misperception can result in erroneous judgments. Participants who misperceive the simulated space would probably be unhappily surprised at the outcome of the project. The entire process of discovering and evaluating a space with this simulation could be detrimental to its intent of improving the communication between the designer and the client.

It is therefore imperative we address these basic questions: just how well does this new tool represent architectural spaces? How valuable can our judgments of virtual spaces be in predicting our judgments of real spaces? Where are the weaknesses and strengths of this simulation tool?

The purpose of this study is to explore and determine the accuracy of virtual interfaces in simulating the basic characteristics of architectural spaces and to evaluate to what extent our perceptions of virtual and real spaces coincide. Hopefully, this study will help explain the nature of the differences, if any, in the perceptions of virtual and real spaces. These results will, for the design community, guide them in their use of this technology by highlighting its existing shortfalls and strengths. To the hardware and software developers, the same results will indicate which aspects of the technology need improvement most urgently.

CHAPTER 1. ARCHITECTURAL REPRESENTATIONS

Architects are in the business of designing spaces through the manipulation of real and virtual surfaces. During this design process, they need to continually evaluate the spaces they are creating among themselves and with their clients. They do so by using various techniques of representation of space. A partial list of these techniques include the perspective sketch, line drawings (plans, elevations, sections, isometric views), scale models, photo montage, computer animation and samples of actual building material.

Architects use different methods of representation at different stages of the design process, depending on what specific decisions need to be made. This is because representations are generally only good at telling one part of the story well. As the project evolves, decisions about different aspects of the design are made, at each point using a suited form of representation.

There are many phases in the development of an architectural project, from the "conceptual" to the "detail and finalizing" phase. At the beginning of the project, in the conceptual phase, the designer and the client discuss initial design ideas using rough sketches representing the basic geometric forms of the project. As the ideas mature, the project enters a new phase and gradually develops a vocabulary of forms. The conceptual geometric shapes become spaces made of surfaces and openings, and a first sense for the interior space takes shape.

At this juncture, the designer and the client need to make decisions about the way the spaces will "function" and "feel". More specifically, they need to evaluate (1) the sizes of the individual spaces, (2) the relative configuration of the spaces to each other and (3) the qualities and attributes of the individual spaces. These are spatial evaluations which, to be made perfectly accurate, would require that one be *present* in them. Ideally one would actually experience them as real places by walking through them. Clearly however, this solution is not realistic. It is inflexible, expensive and time consuming. As a result, architects have had to rely on representations of these spaces.

Historically, the representation technique around which these decisions have taken place is the scale model. Generally constructed entirely of one building material, such as cardboard, this scale model includes only the main architectural space elements, such as the walls, the openings, the floor, the ceiling and a removable roof (for better observation of the interior). If there are stairs in the project, they are often simply represented as ramps. The simplicity of the model and the lack of distinction between building materials helps decision makers focus on the main aspects of the space.

Scale models have been predominant tools for representing the feel of interior spaces for many years. However, there is a significant shortcoming in the use of scale models. They are small. As a result, to evaluate the "feel" and "function" of the space, users have to imagine or project themselves into the miniature model. While most of us are quite capable of *imagining ourselves in* these scale models, it is quite a different experience from *actually being in* them. How can it be certain users get an accurate sense for their own scale when they imagine themselves inside the model? And to make things worse, the problem is further compounded when the user has to imagine moving through the spaces.

Fortunately, advances in technology have brought considerable improvements to the problem of scale and movement in scale models. The first such improvement was the introduction of miniature cameras into the scale models. Typically, these cameras move about at eye height in the model, and their image is transmitted to a television monitor. More sophisticated versions have an apparatus which allows participants themselves to control the movement of the camera around and about the model (Bosselman 1987, Sasanoff 1967). With this new technique, the task of understanding the spaces is greatly simplified because it removes the need to imagine oneself in small scale. As a result, evaluations about the modeled spaces have become more reliable.

While the use of mini-cameras was being developed, parallel advancements in the field of computer graphics and animation began replacing the role of the physical scale model. Computer models are more flexible because they can be modified at very little expense. For many years, this technology suffered from limited graphic rendering and computer speed. Early computer models consisted of line drawings, and the "hidden line" was not hidden. Faster computers made it possible to display solid shading of polygons, and still faster and better programs added advanced rendering techniques, such as ray tracing, transparency and shadows. While these sophisticated renderings take a lot of time to compute, when transferred onto video tape, they offer convincing walkthroughs (batch computer animations).

As the power of computers increased, the rendering time decreased. Soon, given a simple model, it became possible for a viewer to change their viewpoint in a computer model in near real time, that is , 10 to 20 times per second. One such program is Virtus Walkthrough™. By sacrificing high rendering detail for speed, it allows viewers to move their viewpoint throughout the model in real time on the Macintosh platform. More sophisticated platforms, such as the Reality Engine, which runs on the Silicon Graphics workstation, are fast enough to render very high realism scenes in real time.

There is no doubt that both the advancements of technology in the mechanical field (mini-camera) and the computer field (real-time walkthrough) have improved the task of representing interior spaces. They allow viewers to better understand how the modeled spaces would feel because they have placed the position of the viewpoint inside the model, they allow the viewer to choose how they want to see the spaces, and they facilitate viewers in understanding how it would feel to move through the space.

However, this viewing perspective has created a new problem which did not exist before, and it has displaced a second. The problem it has created is that it has reduced the 3 dimensional spatial information of the scale model onto a 2 dimensional medium. In effect, the specificity of spatial information which was available in the scale model, now has to be interpreted from a 2 D representation. It has also displaced the problem of scale, rather than resolve it. While we take much of this for granted, we perform an important transformation of scale when we look at television monitors. We understand that the actual size of objects seen on the monitor have no relationship to the size of the monitor itself. The view of a building which only fills half of the screen is understood to be many tens of feet tall.

Furthermore, the participant is only remotely coupled to the model because they control their viewpoint using a kind of joystick device. They are more coupled to real settings and to a certain extent to scale models because they change their viewpoints by moving their head and their body.

For the reasons listed above, monitor-based representations are far from perfect for describing the "feel" of proposed architectural spaces. To make them closer to perfect, they would have to offer a more convincing illusion of depth, a more appropriate sense of scale and a greater coupling between the process by which people explore spaces in simulated and real environments.

A New Technique for Representing Architectural Space.

There have been tremendous advancements in the field of computer rendering in the last several years and a merging of technologies which together, could solve all of the problems related to existing forms of computer based simulations. This new technology is called "virtual reality" for some, "cyberspace" or "virtual environments" for still others.

Virtual environments create a powerful sense of immersion within a computer model. Participants are immersed and surrounded by information which is to scale and which is 3 dimensional. The interface is very intuitive to use for exploring virtual environments because it is tightly coupled to the way people explore real environments. Viewers can look around in the model by turning and moving their heads, as they do naturally in real spaces. Because of the specific attributes of virtual interfaces, people develop a sense of actually being somehow present inside the model. And with this sense of presence, viewers could potentially, for the first time, perceive the modeled spaces as they would the real spaces. Virtual environments are poised to be the perfect representation tool for helping architects make decisions about architectural spaces before they are built.

CHAPTER 2. DEFINING VIRTUAL ENVIRONMENTS

One of the astonishing and distinguishing features of virtual interface technology are participant's response to it as a place. While experiencing virtual worlds, they can be heard saying "I wonder what's in *here*" or, "*where* am I now?", and afterwards, their comments about their experience often start with the words "when I was *there*". "*Here, there and where* " are responses to a place. People who experience virtual worlds feel as if they are really there, in the virtual models. Few other presentation mediums, be they cinematography, television, books, music or architectural renderings can generate such compelling impressions of being in a place.

There are at minimum six fundamental components to virtual interfaces which are responsible for creating the effect of being in the models. In general, virtual environments consist of a stereoscopic display, a device which tracks the position of the observer's head, a device for interacting with the model, a very powerful image rendering computer, a computer model and the computer program which makes the interaction possible. These components can take on very different forms, depending on the make of the product, and they can be used in many differing combinations.

Virtual interfaces are not limited to the visual modality. There exist very effective forms of 3 dimensional sound, as well as more rudimentary forms of tactile feedback. These modalities can be of considerable help for acquiring an accurate perception of space. However, their complexity is such that they cannot be included in this study.

Stereoscopic Display.

There are several very different stereoscopic display solutions in existence today. They range from the more public "retro-projection" techniques to the more personal techniques such as the Head Mounted Display (H.M.D). In the retro-projection display, the observer(s) is(are) surrounded by several large screens. Two images of the same scene (one for each eye) are projected from behind the screens. By wearing special stereoscopic glasses, observers have the illusion of seeing the objects in depth.

The H.M.D, often referred to as "eyephones", is another common form of display. It is this display medium which will be used for this study. The eyephones consist of two small color C.R.T monitors (one for each eye) and optics for magnification. They are set inside a head-mounted apparatus which looks like diving goggles (see Appendix D: Interface Hardware). Each eye has a field of view of 75° and combined field of view of 90°. The overlap between both eyes is 60°. This overlap allows for the necessary convergence of the eyes required in order to have a good sense of depth. The peripheral field of view beyond the displayed image is prevented from receiving any visual stimulus from the exterior by the black rubber sidings in the goggles.

The resolution of the eyephones are 1/4 th that of N.T.S.C television monitors. At that resolution, one can clearly see the individual screen cells. When the eyephones are put on, the eyes are within about 1 inch from the optics. Fortunately, this is not a big problem because the light which comes through the eyephones is collimated, that is to say, the light is parallel, and it appears to come from an infinite distance. As a result, one tends to focus more easily on the model than on the screen itself.

A Position Tracker.

The position tracker is a device which measures the rotation (Yaw, Pitch and Roll) and translation (x, y and z) of any object to which it is attached. It samples this information many times per second. The tracker is usually attached to the observer's head. It can also be used to track the position of other parts of the body, such as the hands (V.P.L's Dataglove™) or even the whole body (the Bodysuit™). There is a great range in tracking technologies from the more "mechanical" ones such as the Boom™, to more "electrical" solutions using ultrasounds, infra-red light, electromagnetic fields, or multiple cameras. What makes these approaches different is their tracking range, their ability to tolerate interference, their precision and their cost.

For this study, I will be using V.P.L's Polhemus™ tracker. In this configuration, a "parent" source emits an electromagnetic field a few feet in circumference. A "receptor" located on the eyephones and well within the magnetic field identifies the exact location and rotation of the observer's head. Because the Polhemus has such a short working range, it can only tolerate small translations of the body. For traveling larger distances, the observer has to use an interaction device.

Interaction Devices.

After head-tracking, movement is probably the form of interaction most important for conveying a sense of presence in virtual environments. Ideally, it is preferred that participants physically walk through the modeled environment. At the University of North Carolina at Chapel Hill, researchers have developed a treadmill which allows participants to "physically" walk in the virtual environment. In this way, the users always stay within the reach of the tracking sensor, and yet they have the kinesthetic feedback of physically walking. Each real step moves their viewpoint one virtual step. Researchers are also developing a tracking system which would allow the participant to walk in the virtual space by actually walking in a large real space (Optical trackers). Both of these techniques enhance the perception of space because, in addition to the visual (and potential auditory depth cues), users also get the kinesthetic feedback so essential for making estimates of distance.

Since the tracking devices at the H.I.T.Lab are of the type with a limited range, a movement interaction device is required to replace the act of walking. These devices simulate movement by moving the position of the viewpoint through the model while the observer stands still. There are a number of devices to do this, including the Dataglove, the joystick and the Spaceball™. In the case of the Dataglove, the participant "gestures" a pointing finger in the direction they wish to move. This action is interpreted by the program to advance the location of the participant's viewpoint , thereby giving them the illusion of motion. The joystick and Spaceball are variations which work principally the same way.

For this study, the interaction device that will be used for movement is the Spaceball. This device is generally used to affect the rotation and translation of objects in three dimensional models. In this study, it will be used to affect the observer's viewpoint. The Spaceball is an uncommon device for controlling the movement of the viewpoint in virtual environments. There are other devices which are better suited. However, only this device can logically function in all the test conditions of this study (for more information, refer to Appendix D: Interface Hardware).

The Fast Rendering Computer

Along with the quality of the graphics, the most important criteria for computers used for displaying virtual environments is the speed at which they render the images. This is referred to as the update rate. It is the speed with which the computer can calculate and render each new view. Although there has been no definitive study as to the minimum update to sustain the illusion of presence, most researchers would agree that 7 frames per second is an important threshold, below which the intervention of conscious awareness is often inevitable.

Since the data base of these virtual environments are models, the unit of measure for the speed of a computer is the number of polygons it can render per second. The polygon is a surface made up of three vertices, like the triangle. A six-sided cube has 12 polygons. The greater the complexity of the model, the higher the polygon count. Small computers can render models made up of a few polygons many times per second, whereas faster ones can render millions of polygons per second.

The computer at the HITLab is the Silicon Graphics 320 VGX workstation. It is rated at 1,000,000 polygons per second. Since it needs to render two different scenes, one for each eye, the actual polygon count is 500,000/second per eye. And if the number of updates required per second is a minimum of 10, that means it can calculate at best about 50,000 polygons/second. These figures are for ideal conditions. In actual practice however, because the same computer has to run the interaction program and interpret the tracking data, the update rate is much lower. In the particular conditions of this study, it was found to be able to render 4000 polygons at 8 frames per second per eye.

The Model.

Many computer modeling programs can be used to build models for virtual interfaces. There are some limitations however as to the kinds of objects which can be created. At the time of this study, spline and bezier curves are not supported by the rendering software.

Neither are higher order rendering techniques (ray tracing, phong) and sophisticated lighting conditions. The only forms available for building a model are wireframe or flat shaded and simply colored polygons.

The Computer Program.

The virtual interface computer program continually interprets the position tracking data and the movement interaction data together with the model data base in order to render and display the appropriate view of the model to the eyephones. There are several commercially available packages (V.P.L microcosm, Sense 8), as well as many locally fabricated software programs in various university laboratories. Due to the specificity of the study at hand, a separate rendering program was designed by Marc Cygnus at the H.I.T.Lab. It is a "hard coded" program, that is to say, it can only work for this particular study (V.E.O.S, the operating system designed at the H.I.T.Lab, was not far enough along to be used reliably at the time of this study). The complete virtual interface configuration for this study is summarized in Table 2.1.

Table 2.1 - Virtual Interface System at the H.I.T.Lab.

Eyephones	VPL stereoscopic color CRT displays
Resolution	1/4 th NTSC
Field of View	75° per eye, 60° overlap, and 90° overall
Computer	Silicon Graphics VGX 320 workstation (1,000,000 polygons/second rating)
Modeling Software	Alias. Objects made of polygons only.
Interaction Software	Designed by Marc Cygnus. Renders flat shaded polygons. There are 2 directional and 1 ambient light source.
Tracking device	VPL DataBox for head tracking (30 times/second)
Interaction Device	SpaceBall, in conjunction with the rotation direction of the tracking device in the "Tracked" condition
Update Rate	≈8 - 10 frames per second for a 3800 polygon model (Including the multiple light sources, the model rendering, the tracking data and the interaction device data).

How It All Works.

When a participant puts on the eyephones, (s)he sees the interior of the computer model. Because the eyephones are equipped with position trackers, the computer can be updated as to the exact location of the participant's head at any one time. With this new information, it can render newly appropriate view of the model. In effect, when the participant flexes their knees, the tracker signals to the computer that the participant has lowered the position of his/her head. Simultaneously, the computer renders a viewpoint into the model which appears to be lower, thereby replicating the participant's expected visual changes in the physical setting. Similarly, as the participant turns his/her body around completely (180°), the view they have of the model is simultaneously updated so that what was behind them in the model is now in front of them. For every movement of the head, there is an equal change in the viewpoint of the computer model. As a result, everywhere he/she turns, the participant finds him/herself "surrounded" by the model. This very tight coupling between their physical movements and the updated view of the model gives the participants a sense of *presence* within the model. It makes them feel as if they were *immersed within* the virtual environment.

Using Virtual Interfaces to Simulate Architecture.

Everything about virtual interfaces seem to indicate that they would be perfect tools for simulating architectural spaces. They seem to satisfy all of the criteria for the perception of motion and space, as defined by Appleyard (Appleyard, 1964):

> "A. Apparent self-motion : speed, direction, and their changes (stop-go, accelerate-decelerate, up-down, right-left).
> B. Apparent motion of the visual field : passing alongside, overhead, or underneath; rotation; translation ; spreading or shrinking of outline or texture ; general stability or instability ; apparent velocity or lack of it.
> C. Spatial characteristics:
>
> > (1) Presence and position of enclosing objects or surfaces, their solidity and degree of enclosure,
> > (2) General proportions of the space enclosed; scale with respect to the observer; position of the observer,

> (3) Quality of the light which makes the space apparent; intensity and direction,
>
> (4) Relationship of spaces in sequence : jointing and overlapping,
>
> (5) Direction of principal views, which draw the eye toward different aspects of the spatial enclosure."

The convincing sense of presence and of being in the models are exactly the qualities required for assessing the feel of architectural spaces. These are also the attributes missing in the other forms of representation.

The problems plaguing the previous forms of space representations were scale and depth cues. Because the models were viewed on a 2D screen, the third dimension (depth) of spatial information was diminished. The stereoscopic eyephones used in virtual interfaces recreates the third dimension of space. Scale is no longer a problem either because the position tracking of the body is a continual confirmation of one's presence and scale relative to the model.

As they exist today, virtual environments could help designers and their clients make more accurate evaluations about the basic spatial characteristics of their projects because they would perceive virtual spatial information the same way as they do real spatial information. They could walk about and explore the virtual space as they would the real space.

Virtual environments would seem to be the perfect representation tools to replace the scale model and the monitor-based computer walkthroughs because those, at best, require users to *imagine* being "there" by *mentally projecting* themselves into the space. In virtual environments, participants are intuitively "there". No conscious effort, transformations, or projections are required to "get a feel" for the modeled spaces - users interact with the virtual environments almost as naturally as they do in real environments.

Concerns.

While it is clear that virtual interfaces can create the illusion of being present in a computer model, very little is known about the representativeness of virtual spaces to real ones. The technological components are all designed to simulate spaces so that they are perceived in the same way as real spaces; the eyephones display the model in 3D, the position-tracking devices map the viewpoint of the observer one-to-one with the movements of their head, and the model is at human scale. Nonetheless, it is unknown as to whether similar spaces would actually be *perceived* to be the same in both virtual and real environments.

While the potential for using virtual interfaces as representations of architectural spaces is clear, their risk of leading to misperceptions must not be overlooked. Indeed, if people use them with the conviction that their perception of the virtual space is the same as it would be of the real space, when in actuality it is quite different, it could lead to errors of judgment during the decision making process. If distance were misperceived, spaces might be judged too big when if fact, in real life, they are just the right size. If the layout is misperceived, people could be very upset when they encounter the finalized project.

Clearly it is important that here, as with any new simulation technology, virtual environments be evaluated for their representativeness. More specifically, to make virtual environments a viable alternative for representing architectural spaces, people must be at least as accurate in their spatial perception as when viewing a real-time walkthrough.

CHAPTER 3. MEASURING SPATIAL PERCEPTION

As discussed in Chapter 1., the spatial representation should allow people to make accurate judgments about (1) the sizes of the individual spaces, (2) the relative configuration of the spaces to each other and (3) the qualities and attributes of the individual spaces (Fig. 3.1). The spatial perception of participants needs to be measured separately for each of the three judgments.

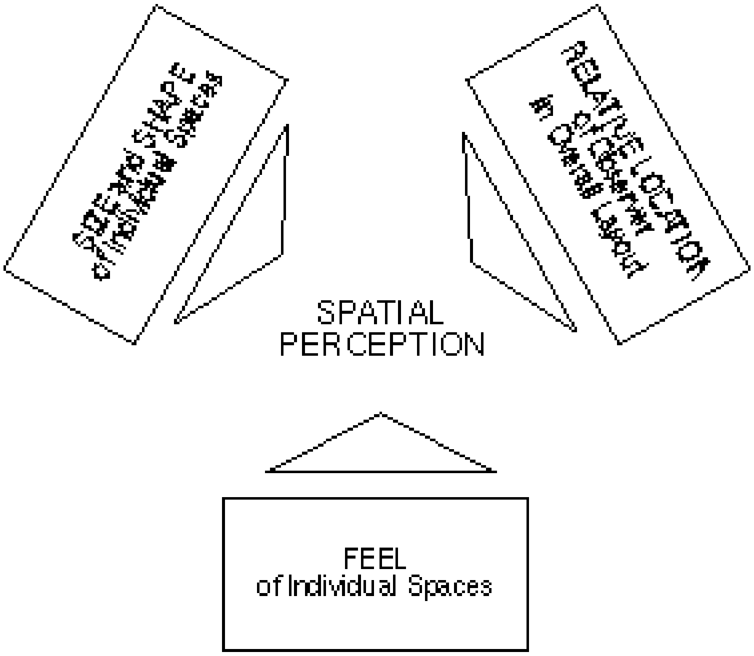


Fig. 3.1 - The three components of spatial perception at this early junction in the design process

Size of Volume.

The most basic attribute of space is its shape and size. The simplest way to measure people's perception of room sizes is to ask them directly. Most people are quite comfortable expressing distances as a function of other distances. A common expression for describing the size of a room is to say that "it is twice as large as my kitchen", or "I could line 3 couches up from wall to wall". Very few people feel they can be accurate in expressing distances using a metric system, such as feet or meters, because metric distances are not immediately intuitive. Passini discusses studies which show that, "on the whole, people are not very accurate in estimating routes in metric units, although they may be quite able to judge relative distances. Even when distances are compared in non-metric terms, certain complicated but relatively consistent distortions occur" (Passini, 1984). For this reason, most psychophysical studies use a "ratio estimate technique", such as Sadalla's Room Size experiment (Sadalla 1984, Allen 1978). Although the "ratio estimate technique" is helpful, it leaves room for quite a bit of imprecision, and certainly more than can be tolerated for this kind of study.

To have a greater accuracy in distance data, the participants can be pre-selected so that only those who are particularly good at estimating distances in absolute lengths take part in the study. For this experiment, I invited professional space designer because have ample experience estimating lengths of building materials and interior spaces. The task of estimating the dimensions of virtual spaces should be easy for this group because it is something they do often in real environments.

Spatial Orientation.

Also of great importance during the early phases of design process is the ability to evaluate the relationship of the overall spaces. The way one feels in a particular space is partly affected by the perception one has of that space's location within the overall project. Being in a hotel suite at the top floor of the building is simply not the same as being in a similar suite at ground floor.

When people experience a new environment, they unconsciously build a kind of "mental map" of the new space. This mental map, often referred to as a "cognitive map", is a way of storing spatial information in memory. It is a survival mechanism which allows us to find our way in unfamiliar environments. The cognitive map is continually refined and updated as the environment is re-explored.

A good way to measure the accuracy of people's perception of their place in the overall layout of a virtual environment is to study the cognitive map they form of these spaces.

The most straightforward approach to measuring a cognitive map is to ask people to sketch a plan. Generally, the experimenter asks the participants of the experiment to sketch rather hastily a map which represents a plan view of the place in question (Canter, 1977). This is an information rich method for measuring people's understanding of spaces. It includes the size of all the individual spaces, their location relative to each other as well as particular details and landmarks. But while this approach would measure the exact information of interest to this study, it has several important flaws.

An important concern is the process by which people go from having a 3 D cognitive map or memory of the space in their minds, to transcribing it as a 2 D plan view. A person might have a perfectly accurate cognitive map but might be unable to accurately translate that information on paper. If nothing else, this process requires a particular kind of skill without which the interpretation of the sketches become meaningless.

Another concern is that cognitive map sketches are measures of more than simply people's spatial understanding of an environment. To begin with, they also are a measure of a person's memory of a space. The sketches are drawn after the space has been visited. This means that the accuracy of the sketch is also a function of the variation in people's ability to remember spaces. The *memory* of a space is not of primary importance in this study. What is of interest is the measure of peoples perception of virtual spaces *while they are in* them. Furthermore, sketches also measure people's ability to draw. A participant who has a good sense of what a certain place is like, but who has difficulties drawing plan views to scale, will appear to have an inaccurate cognitive map.

And finally, the sketch technique is difficult to analyze. The sketches have to be compared without regard to shrinkage, expansion or rotation. To do this accurately, a specially dedicated computer program is necessary such as the *Congru* computer program, a Multidimensional scaling analysis (Allen 1978).

There is an indirect method for measuring people's cognitive map which is easier to measure and which does not suffer from the confounding sources of error present in sketches. It is the "point in the direction" technique. In this approach, participants move about a space and at specific moments, they are asked to stop and to point in the direction of a specific object or places they saw previously. Since the objects are out of sight, participants have to extrapolate the location of the target using their cognitive map. In some studies, after pointing the direction, participants then must also estimate the straight line distance from themselves to the target (Gärling 1981, Okabe 1986).

There are many advantages to using this technique: it measures people's understanding of the spaces immediately, rather than their memory of the spaces, it is a relatively common task - just about every one has at one time or another given instructions by pointing the way, it does not require any transformation of spatial information from a 3 dimensional space to a 2 dimensional medium and finally, it is easy to measure - the results of the pointing task are expressed in angles and the results from the distance task are expressed in feet or as a ratio.

The shortfall of the pointing technique is that it contains less information than the sketch. It only measures peoples' estimates for the relative location of objects and spaces. Unlike the sketch, it does not show or represent relative sizes of spaces, nor does it show the path a person might take to get to the target.

There are advantages and disadvantages to both the sketch and the pointing methods. Although the pointing task is only a partial indication of people's cognitive maps, it is better suited for this study because it offers more specific quantifiable data. However, I also asked people to draw a sketch but the results were not statistically manipulated. They serve to verify the pointing task results and as to explore for unusual trends or findings.

Descriptive - Feel of Individual Spaces.

The third important perception people need to make accurately during the early design phase is that of perceiving how the spaces feel. Already at this phase, the basic characteristics of the space can make them feel large or small, claustrophobic, public or private, open and inviting or chilling. While the importance of how a place feels is the overall goal of a successful simulation, it is the most difficult perception to measure. There are clearly no objective values attributable to the qualities of spaces.

Kenneth Craik is a professor in the behavioral science department at the University of California at Berkeley. Professor Craik worked closely in conjunction with Peter Bosselman, who is the director of the Berkeley Simulation Laboratory at U.C.B. Together they developed a long list of methods for measuring people's perception of urban spaces (see Table 3.1).

Table 3.1 - Spatial Perception Measurements

- Free description
- Adjective checklists
- Activity and mood checklist
- Q-sort description
- Ratings
- Thematic potential analysis
- Symbolic equivalent
- Multisensory equivalents
- Empathic interpretations
- Social stereotypic cues
- Beliefs about human consequences
- Viewing time
- Motational systems

These are questionnaires administered to the participants after they have visited the test site. They vary in their directness. The first approaches, such as the Adjective Checklist, ask the participant specifically how they perceive the environment. Other approaches measure people's perception of space in more indirect ways. (For a complete description of these methods, refer to Craik, 1970).

The adjective checklist is the most common measure for tasks which require quantitative estimates of people's spatial descriptions (Bosselman 1987, Craik 1970). This technique consists administering a list of bi-polar adjectives. The participant selects all the adjectives which apply to the test space. The results of the experimental environments can be compared to those for the real place. Their level of correlation becomes the measure of "goodness" of representativeness of the simulation condition.

There has been extensive research as to the adjectives which are appropriate for describing all existing spaces (Pedersen 1978, Kasmar 1970). Kasmar has conducted a comprehensive experiment to develop a "usable lexicon of environmental descriptors". She came up with a list of 66 polar adjectives. I used her list as a basis for the checklist, although it was greatly shortened to a more manageable size for the short length of this study.

One of the unavoidable difficulties with the adjective checklist and any other method for measuring the "feel" of a space is the enormous variability between people. To compensate for this problem, a very large subject pools is needed. Unfortunately, the scope of this study made it impossible to have such large number of subjects. Although this was feared to be a problem, the results nonetheless suggested that there were sufficient numbers of participants to reveal possible trends.

Other Methods.

Many evaluations of architectural simulations have employed yet another method of measure for "goodness". This approach is a form of general measure. It is related to people's behavior in the spaces. The idea is that people's behavior in spaces is very much a function of the space itself, and what it affords people to do in it. If two spaces are similar enough, such as a virtual environment and a real environment, then people's behavior should be similar as well.

One such measure is the "behavioral map". This is a kind of log of a person's behavior in a space. It includes the person's movement in the space, where they spend their time, doing what kind of activity. It is most commonly used in psychiatric wards (Ittelson 1970, Weiss 1962).

Sasanoff and Bechtel both studied movement of people in spaces (Winkel 1965, Bechtel 1967). Bechtel used an "invisible" technique for measuring movement in a museum. It consisted of covering the floor of the museum with pressure sensitive tiles. As visitors walked about, their paths could be immediately and accurately recorded. In the Sasanoff study, students disguised as museum guards drew the visiting path of selected visitors.

The advantage of measuring movement is that, of all the methods mentioned previously, it is the least obtrusive one. The results are less tainted by the participant's awareness of the study. The problem however with behavioral analysis is that people's behavior are complex and they vary tremendously from person to person. Furthermore, results from an analysis of movement would not indicate where the problem areas are.

Measuring Spatial Perception - Conclusion.

The results of the three methods described for evaluating peoples perception of space will serve as the basis for comparing virtual and real space. If there is a high correlation between the two, then it can be concluded that virtual interfaces are accurate representations of real spaces, and that they can be used as architectural representation tools with a good conscience. Should there be a significant difference between the perception of virtual and real spaces, then users of virtual interfaces should be warned about the risk of misperception. The results should also point to areas where it is most important to make technological improvements.

In addition to the three measures of spatial perception, participants will also have a chance to express their impressions about the interface directly. This can lead to problem areas overlooked by the tasks. The questionnaire will encourage participants to discuss what it is about the interface which makes it easy or difficult to do the various perceptual tasks. They will also be asked to rate the value of the tool for professional use.

CHAPTER 4. THE HYPOTHESIS

The Hypothesis.

Virtual interfaces, in their existing technological condition, represent real spaces well enough to replace the real-time walkthroughs. They allow designers to make evaluations of individual volume sizes, overall volume layout and individual volume descriptions at least as accurately as those made when viewing a walkthrough representation.

Review of the Literature.

Virtual Interface Technologies are very new, and while they do permit the simulation of spaces, to this day, there exist no formal investigation of the representativeness of virtual spaces for architectural applications. Some institutions already use virtual interface technology for the purpose of architectural simulations. One such institution, the Chapel Hill simulation laboratory at the University of Carolina, has been working most closely with designers and architects in the development of their technology. But to my knowledge, they have done no specific study which actually evaluates the "representativeness" of virtual architectural spaces.

While there have been no previous studies on this topic, there have been numerous informal studies and observations at the H.I.T.Lab which suggest the location of problem areas. The observations were made possible because of the extensive demonstrating which takes place at the laboratory.

With regard to the perception of distances, there have not been any informal studies. In general, it has been assumed that people perceive dimensions of spaces to be the same size as intended since the scale of the model is exactly human scale. The results of this task are the first of their kind, and the findings can only be enlightening.

What has been much more evident during the demonstrations is the extent to which people get disoriented. In the simplest worlds designed at the H.I.T.Lab, participants have all expressed a sense of disorientation. In one such world, TopoSeattle, a 5 square mile portion of Seattle was modeled using real topographical data. It was so difficult for one to know where one was that landmarks had to be added to help people understand where they were. But even that proved to be insufficient. Participants would "fly" far above the model to get a birds eye view, without which they were unable to build a cognitive map of the area. Unfortunately, even as they did so, they would lose their sense of orientation as soon as they came back down into the model.

I have conducted many informal studies that have addressed the issue of orientation. The Globalview world was one such project. It consisted of a simple maze with walls 8 feet in height. Participants moved through it at a constrained eye height, well below the height of the walls. If they were confused about their position, they could, at any time, "jump into" a view from above. They would see themselves from above and in the context of the larger model.

In another study aimed at improving people's sense of orientation, a portion of the real environment was modeled and included in the virtual model. In the PolhemuStudy world, the Polhemus parent source, the pole it was attached to, and a 10 square area of laboratory floor were represented in actual scale in the virtual model. It was hoped that including real space information would help people know where they were in the virtual space.

While non of these solutions proved conclusive, they indicate the concern that it is very difficult for participants to build a workable cognitive map of virtual environments. The limited field of view is speculated to be one of the reasons for this problem. It is quite conceivable that the 90° field of view interferes with people's ability to "build" the cognitive map of their environments. In related studies, Alfano and Michel explored the perception of size as a function of greatly truncated fields of view. They suggest "that the overlap of peripheral and fovea information is necessary for veridical perception to occur, … and that restricting the field of view will interfere with both perception and visuomotor performance " (Alfano 1990).

Another potential source for the difficulty in orientation is the optical distortion of the eyephones. These optics tend to diminish the size of objects in the center of the optics, and enlarge them towards the edges. This is not very noticeable when one looks through the eyephones at a static view (see Appendix E: Optical Distortion). However, as soon as one moves or turns one's head, the environment acquires a sense of plasticity. This plasticity makes straight walls appear to curve dynamically as one turns. This element could certainly be partly responsible for the difficulties people have in orienting themselves.

In the descriptive aspect of spatial perception, there again exists no published results as to the accuracy of the representativeness of virtual environments. Relying on informal studies at the H.I.T.Lab., it has been found that people not only have a sense of being in the models, they also speak of experiencing the model. In the Poisson world, there is a large pool of water, surrounded by mountains. The participants drop down to the bottom of the pool and finds themselves in a sort of grotto. Then, a large swordfish enters the space from a crevasse. It makes its way around the grotto and passes inches away from the participant who cannot resist outstretching a hand in an attempt to touch it. People who have been in this world acquire a very distinctive sense for the kind of environment it is. They have no difficulty to describe the "feel" of the space because the immersive nature of virtual environments made them feel as if they were present in the model. This sense of presence is instrumental to being able to judge how the space feels. For this reason, I believe that people's perception for the qualities of spaces will be more accurate in the virtual environment than in the walkthrough presentations.

CHAPTER 5. DESIGNING THE EXPERIMENT

The Experiment Conditions.

Three experimental categories are required in order to measure the extent to which virtual environments succeed in providing accurate perceptions of the basic characteristics of architectural spaces: an existing real-time computer walkthrough, a virtual environment and a real setting. By comparing both the category of virtual interfaces and the best existing method of spatial representation to the real setting, any differences between the two simulation categories can be "relativized" to the real one.

In the walkthrough category, the viewer looks at a television monitor to see the modeled space. The viewer can move their point of observation in the model by using the Spaceball movement interface described in Chapter 3.

There are at minimum two factors which differentiate the walkthrough from virtual interface: the stereoscopic eyephones and the head tracking. To isolate which one of the two factors will be responsible for potential differences between the two categories, a third intermediary condition has to be interceded. This third condition, which will be called the "Fixed" condition, includes the stereoscopic eyephones but not the head tracking device. To distinguish between the categories and this new condition, the computer walkthrough category will be referred to as the "Monitor" condition. The virtual interface will be called the "Tracked" condition, and the real setting will be called "Real" condition.

The control of the viewpoint is the same for both the Fixed and the Monitor conditions. However, whereas in the Monitor condition viewers look at a monitor, participants in the Fixed condition will be looking through the stereoscopic eyephones. Similarly, both the Fixed and the Tracked condition use the eyephones. However, in the Tracked condition, participants control their viewpoint with the head tracking device.

The four experimental conditions are then the (1) Monitor condition, (2) the Fixed condition, (3) the Tracked condition and (4) the Real condition.

Design of Experiment.

The study consists of evaluating three simulation conditions against the control group condition (the Real World Setting). The most common approach is a complete random design (C.R.D). All participants experience all conditions in a random order. The advantage of such an approach is that it does not require very many subjects to generate statistically significant results because the variation due to the subjects is taken out of the error term. Another advantage is that it compares the predictability of the simulations directly. Those participants who view the real setting after having experienced it in the simulation condition can immediately confirm the differences between the two environments.

Unfortunately, there are two major drawbacks to the complete random design. The first is one of inconvenience. The Real Setting test site, the Henry Art Gallery, is far from the laboratory where the simulation conditions are to be conducted, and, because it is a public space, the hours available for the experiment are limited to one afternoon.

The second problem is related to the tasks. Since the space that is being evaluated is supposed to be the same one, in the real and the simulation conditions, participants would benefit too much from the order effect. By the time they visited the site a second time, it is feared they would be already as good in their estimates as they could ever be. There would not be any variation to measure.

The alternative design is a random blocked design. Each participant group only experiences one of the four conditions. This design is much easier to administer. The disadvantage of this design however is that the variation due to subjects cannot be taken out of the error term. It makes it much more difficult to find significant differences.

One approach to increasing the chances of finding significant differences, is to have a large number of subjects. However, given the limited length of the experiment, this will not be a viable alternative. Another approach is to control the potential variation among the subjects by selecting a homogeneous subject group. Architects are a homogeneous subject group because they are all very familiar with the tasks required in this study. If the participants are limited to this group, the variation in the results can be attributed more to differences in the display conditions differences in the subject's ability to do the tasks. This does imply that the results of this study can, strictly speaking, only be applied to this group of people, and not to the general public.

It was suggested that, under normal conditions, each group needed an absolute minimum of 5 subjects, below which the variation in individual differences would hide any significant differences due to the display conditions. To strengthen the statistical value of the results, I calculated I would have time to do 7 participants for each condition (The limiting factor was the number of subjects that could be run in one afternoon at the Henry Art Gallery). As the study came to an end, it was clear that I would have to settle for 6 participants per condition, for a total of 24 subjects.

Recruiting Participants.

To qualify for participating in the experiment, subjects have to be professional space designers, or graduate students or professors in the field of architecture. Although graduate students might have less professional experience than the other members of the group, they were nonetheless included because of their more flexible schedule; they could more easily take part in the Real condition which could only be conducted during working hours.

To recruit participants for the simulation conditions, I sent invitations describing the experiment to a variety of architecture firms in the greater Seattle area. The intent was to invite as broad a range of participants as possible so that as many firms could get involved in the process of shaping this technology. Only those who responded that they were particularly open to new technologies were asked to participate. For the Real condition, flyers were also displayed in the architecture department on the campus.

Due to practical limitations, the groups were not completely similar across conditions. Half of the participants in the Real condition were graduate students who had potentially less experience in doing the estimating tasks than their professional counterparts who were in the simulation conditions. Also, the study could not be run in a completely random fashion. All the Real condition participants had to view the real space in one afternoon. The participation of the subjects in the simulation condition was spread out over 7 evenings, and the display conditions were picked at random between the Monitor, Fixed and Tracked conditions every time. It is hoped that the integrity of the experimenter and the way the experiment is conducted should suffice in alleviating concerns about the "evenness" under which the study is conducted.

Designing the Tasks.

Participants' estimates of room sizes vary as a function of the size and shape of the volumes, as well as from the effect of increased familiarity with the environment. This variation is averaged out by having participants estimate a number of different kinds of spaces for the task. Having participants estimate three of the seven spaces in the museum should be sufficient to generate reliable results. The estimated of length, width and height, are expressed as the percentage of the actual dimensions. This facilitates the statistical analysis. It is also a convenient way to show how people's estimates compare to the actual dimensions.

To have reliable results, participants were asked to do the pointing task three times. These values are expressed as the "error in degrees from actual direction".

After each of these tasks, participants were required to express the ease or difficulty of making each specific estimate as well as their level of confidence in their estimate. This information may support the idea that, if not better than existing forms of spatial representation, at least virtual environments are easier to interpret.

The description questionnaire was administered after the visit. It includes a list of 13 bi-polar adjectives which were selected out of a list of 66 (see Chapter 3). Participants select the more appropriate adjective which describes the main gallery space by circling one of the numbers on the semantic differential scale (see Appendix A: Questionnaire).

Choosing a Site.

Because the focus of this study is to evaluate people's perception of the most basic spatial characteristics, and because the details of spaces can play such a large role in our perception of them, it was important to select a space which was simple, free of associations, and which contained few architectural details. Furthermore, it was important to select a site in which the experimenter can control the elements as much as possible.

Museum spaces are ideal for conducting these kinds of studies because their architectural design is implicitly simple, so as not to conflict with the art on display. They are designed to be neutral, well lit public spaces with a combination of closed spaces for specific exhibits and circulation spaces.

After briefly reviewing locally available museums, several reasons compelled me to select the Henry Art Gallery on the campus of the University of Washington : its proximity to the HITLab, the relative simplicity of the space (which implied that it would not require too many polygons to model for the simulation), its lack of exterior views (which would not have to be contended with), and finally, its appeal as a very special and pleasant space.

The museum is a Beaux-Arts design built in the early 1900's. There are six gallery spaces. Each space has a vaulted ceiling and a large skylight which baths the space in cool white light. The gallery has a main space, by far the most pleasant of all, through which one must pass to visit the spaces at the end.

The study would have to be conducted at a time when there was no artwork on display because it was found that, as can be expected, the art hindered people's ability to focus on the tasks of the experiment. The museum would also have to be vacant, except for the experimenter and the participant. Environmental psychologists Proshansky states that "spaces, their properties, the *people* in them and the *activities* that involve these people represent significant systems for the individual participant and thereby *influence his response to the physical setting*" (Proshansky 1970). Under these constraints, the museum could only be made available one day, from 1 to 5 PM.

There are several drawbacks to the selection of this site for the study. The simplicity of the plan makes the orientation task easier. The little variation in the types of spaces simplifies the estimating task as well. All the galleries are explicitly enclosed rectilinear spaces. According to Thiel, these are all basically the same types of spaces (for a complete description of space types, refer to Thiel's work, Thiel 1964).

The Computer Model - Choosing an Appropriate Level of Detail.

The level of realism of the model depends on the kind of information that one wants to communicate. Since the purpose of the representation is to communicate the most basic characteristics of spaces, the model should only include the most basic spatial establishing elements (SEEs, see Thiel 1964). To determine what those elements should be, I held photographs of the Henry Art Gallery with an outstretched hand and I squinted. I assumed that whatever elements were still apparent must be significant space establishing elements. They included walls, door frames, skylight frames and ceiling and floor trims (Fig. 5.1).

Fig. 5.1 - Photograph of model - Trim detail.

The distinction in surface materials appeared as a color distinction. Details that could not be distinguished were the ventilation grills, light switches, the specific materials of the floors and walls, and a certain degree of detail in the wood trims. They would not be included in the model.

The Computer Model - Elements of Scale.

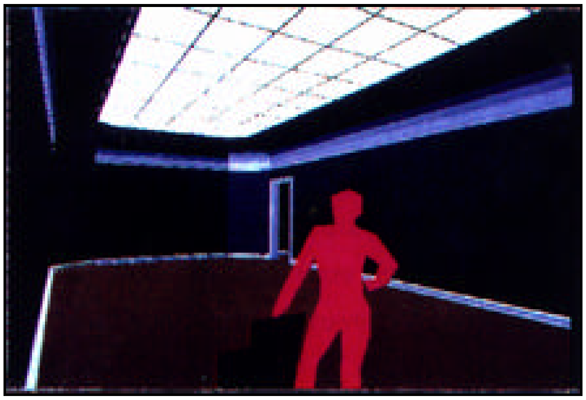


Fig. 5.2 - Photograph of model - Room with scale figure.

Scale is also very important in models. The architectural details alone in the model are not sufficient sources of scale. Traditionally, models include human figures and common household objects to set a sense of scale. In the virtual environment, the lateral movement of one's head is a small but insufficient indication of scale. The model has to include elements of scale as well. Three adult scale figures and one child scale figure, as well as numerous chairs were added to various spaces across the museum to help participants establish an accurate sense of scale (Fig. 5.2).

A little anecdote about scale figures: Before any scale figures were included, people perceived the 8 foot high doorways to be 6 feet and a half, as they often are in homes. When a normal chair was added for scale, is was interpreted to be a child's chair. To override the more pervasive sense of scale from the door frame, an adult scale figure was added. It was perceived to be a child. A small child holding the adult's hand was added to the scene and not until then was the door frame perceived to be larger that normal!

The Model - Technological Limitations.

There are a few important attributes of spaces related to lighting conditions which cannot be rendered and yet which play an important part in defining the character of spaces. With this existing system, a maximum of two directional light sources can be used, along with one ambient light source. Shade and shadows cannot be displayed at all.

The final version of the Henry Art Gallery is a 3800 polygon model. Color is used to replicate as well as possible the colors in the real space and to help distinguish building materials and surfaces. The 9 different colors in the model represent the following groups of spatial elements : the wood trim elements, the walls, the skylight frame, the main hallway floor, the main hallway vault, the main hallway floor, the floor for the rest of the gallery, the chairs and the scale figures.

Two diametrically opposed light sources were required to successfully describe the skylight lighting condition. All of the surfaces were rendered using the "flat" shading technique. In this rendering technique, polygons have only one continuous color.

CHAPTER 6. RUNNING THE STUDY.

Preparation - General.

With regard to all four experimental conditions, the only general concern was that the selected site for the study remain unknown to the participants. It was feared that some participants might be tempted to visit the museum before the study. That, of course, would have tainted the results. Ideally, in a pre-selection process, only architects who had never been to the Henry Art Gallery could have been selected for the study. Unfortunately, most designers have been at least once to the museum. After their selection, care was taken to meet them far away from the test site so as to keep it a mystery.

Preparation - Novelty Factor in Simulations.

For the simulation conditions, additional preparation was required. There is legitimate concern that people who discover virtual environments for the first time are under the spell of the technology's novelty. Furthermore, the SpaceBall they would be using to control their movement is highly unusual, and it was important they have a chance to practice using the device. In general, regardless of the type of experiment, it takes participants a certain amount of time to adapt to the new environment. The environmental psychologist Proshansky suggest that a person's perception of space "is greatly modified as (they) adapt to an environment…" (Proshansky 1970). Proshansky's remark suggests that participants should be allowed enough time to adapt to the simulated environments for their perception of the space to stabilized.

For all of these reasons, a simple model was constructed in which participants could get acquainted with the simulated environments and using the Spaceball. This model consisted of a floor, a few columns and walls and a winding line which represented a path. As participants followed the path, the columns made way for more and more walls and the environment became increasingly inclusive. It became a sort of maze-like space.

Participants' task was to follow the colored path to the core of the maze and back out again until they felt sufficiently comfortable using the interface.

The Setup.

In all simulation conditions, participants were asked to stand because it is a more engaging position in which to discover an architectural space then when seated. Sasanoff, in his study of a film simulation technique argues that the posture can affect the behavior of the participant : "the comfort of *viewing* (sic) the museum while seated in the chair may increase the propensity of the observer to seek a broader rage of experiences than might be the case in the real world experience" (Sasanoff 1966). Since participants were walking in the Real condition, then they at least had to be standing in the simulation conditions.

In the Monitor condition, participants stood in front of a large television monitor. Their distance from the screen was 18". This insured a field of view of 90°, which was consistent with the combined field of view of both eyes in the eyephones conditions. The height of the viewpoint was fixed at 5' 8", regardless of the height of participants. An average eye height was taken because it would have been too difficult to adjust it for every new subject. The fixed eye height was never different from participants' actual eye height by more than six inches. Participants controlled the direction they were looking as well as their movement with the SpaceBall. It was constrained to permit Yaw and Pitch of the view point (no Roll), and movement only in the direction one is facing (no reverse and no sliding sideways).

The Fixed condition the setup was similar to the Monitor condition. The eye height was also fixed at 5' 8". They controlled their viewpoint and movement exactly like in the Monitor condition as well. However, instead of looking at a monitor, these participants were wearing the stereoscopic eyephones.

In the Tracked condition, the tracking device automatically adjusted the participants' viewpoint to the exact height of the participant's eyes. Like in the Fixed condition, they viewed the model through the stereoscopic eyephones. To move in the model, participants pushed on the Spaceball and moved in the direction they were looking just like in the other conditions. However, participants in the Tracked condition controlled the direction of their view by actually turning their head.

The Walkthrough.

In all four viewing conditions, participants visited the spaces in the museum in a pre-determined order. This was to control for variations in results due to differences in the way people explore new spaces. The tour of the museum was such that each space was visited at least once. At specific locations in selected spaces, participants would be asked to do one of the several estimation tasks. Figure 6.1 below shows the path through the museum, as well as the three locations where participants were asked to estimate a room size.

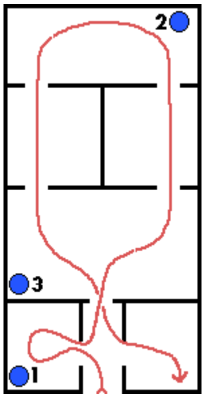


Fig. 6.1 - Locations of size estimate task.

Figure 6.2 shows the location of the three pointing tasks. Because of the narrow field of view in the simulation conditions, all the estimates were made form the corners of the rooms. In this way participants had a little bit more spatial information for making their estimates.

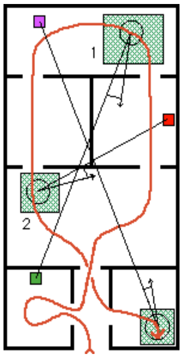


Fig. 6.2 - Location of pointing task and path of visit.

Participants entered or started the visit in the middle of the entrance hallway (space "B" in Fig. 6.3). In the simulation condition, their viewpoint was automatically positioned there. In the real museum, they were accompanied to that point. The next room on the visit was the one on the left (space "A" in Fig. 6.3). It contained a television monitor. Participants were asked to remember its location because they would be asked to locate it later. Then they were asked to move to the corner on the far left, to turn around and to estimate the dimensions of the room without moving from that location (Fig. 6.1). They could describe the dimensions of height, width and length in any order.

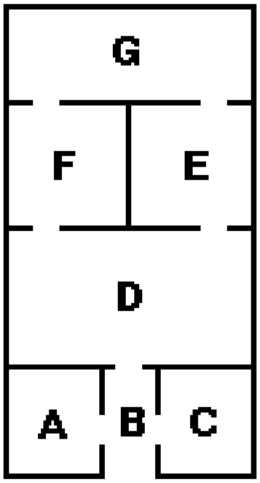


Fig. 6.3 - Plan of museum and labeled spaces.

Then, they were taken back out of the room and into the main gallery (space "D" in Fig. 6.3). In the model, this room had one chair and an adult scale figure holding the hand of a child scale figure. I served as the scale figure in the real museum. Upon entering this space, participants were asked to express their first impressions of the main gallery. Their response was recorded on tape. They were then led to the room ahead on the right which contained the second television monitor (space "F" in Fig. 6.3). They continued on through it until they reached the end room (space "G" in Fig. 6.3). This space had a scale figure next to a chair.

There, as in the first room, they were instructed to go to the corner and estimate the dimensions of the space (Fig. 6.1). Then they did the first pointing task. They were to point in the direction of the first television monitor (Fig. 6.2). Next, they were led to the other end of this room and into the following room (space "E" in Fig. 6.3). This room had one scale figure. They traveled through this room and re-entered the main gallery. Once back in this space, they went to the far right corner and pointed to the second t.v. monitor (Fig. 6.2). They also estimated the size of this room (Fig. 6.1). They were asked to remember this space because they would be asked to describe it in the questionnaire.

Then, they were taken through the hallway and into the last remaining non-visited space (space "C" in Fig. 6.3) where again, going into the far right corner, they estimated the direction to the scale figure and chair in the end room (Fig. 6.2). That concluded the visit.

After the tour of the museum, participants were invited to fill out the questionnaire. This took about 45 minutes and they were asked to do the following task: (1) Draw a sketch plan of the spaces previously visited, (2) describe the main gallery, (3) evaluate the interface, (4) evaluate your sense of presence, (5) participant profile (Appendix: A. Questionnaire). The entire experiment took about 1 to 1 1/2 hours per person.

Notes on differences in set-up: there were a few differences between the Real and the simulated visit. In the Real condition, the position of the participants during the estimation tasks in the end room and the main gallery were slightly different. In general, they were not as close to the corners of the rooms. The need to place participants in the corners did not become apparent until the simulation conditions were run. Also, instead of television monitors, participants in the Real condition had to locate different colored chairs. The monitors required fewer polygons to describe in the model. However, chairs were the only available objects in the real museum.

CHAPTER 7. THE RESULTS.

The measure of the representativeness of virtual environments was measured using three perception tasks. It was also measured in the form of self-reported evaluations from the participants. The results are analyzed and discussed on a task by task basis first, and then they are discussed as a whole.

Size Estimates - Analyzing the Data.

The room size estimating task required participants to estimate the three dimensions, length, width and height, of three different spaces in the museum. Because of the size differences in the three rooms, the results were normalized as percentages of actual room dimensions (1 is a perfect estimate of distance, and .9 is 90% short of the actual length). In this way, it was possible to statistically combine the results of the differently shaped rooms. It was also a convenient way to convey under and overestimates relative to the actual dimensions.

The terms "length" and "width" were used for convenience during the experiment. Participants each had their own definitions for what constituted the "length" or the "width" of the spaces. Some judged that the shorter dimension was the width. Others defined width to be the dimension of a space perpendicular to the entrance. The reversibility in the definition of these dimensions suggests that they can be treated as one relatively shorter or longer dimension. I therefore combined all the horizontal estimates. This doubling of data strengthened the statistical value of the results.

There are two important factors which suggest that the height dimension, on the other hand, should not be combined with the other spatial dimensions of width and length. The first is procedural. To estimate a room's horizontal dimensions, participants generally imagined the number of body lengths required to span the space. This was a difficult task. Subjects had little information as to the size of their bodies laying on the floor because they were standing (or because their bodies were not in the model). The estimate for the vertical dimension was simpler because their standing posture "clued them in" to a large portion of the distance.

The second difference is that, in many instances, participants said that the nature of building construction limited the range of possible vertical dimension. Whereas the widths and lengths of rooms vary, room heights often have standard dimensions because building materials often come in standard dimensions. This limited the variability in the estimates. Of the 144 horizontal estimates (2 dimensions x 3 rooms x 24 participants), only one estimate was exact, representing less than 1% of the total number of guesses. Of the 72 height estimates (1 dimension x 3 rooms x 24 participants), 17 were perfect, about 24%. As a result, the size task results had to be divided into "horizontal" and "vertical" dimension estimates.

Size Estimates - General Observation.

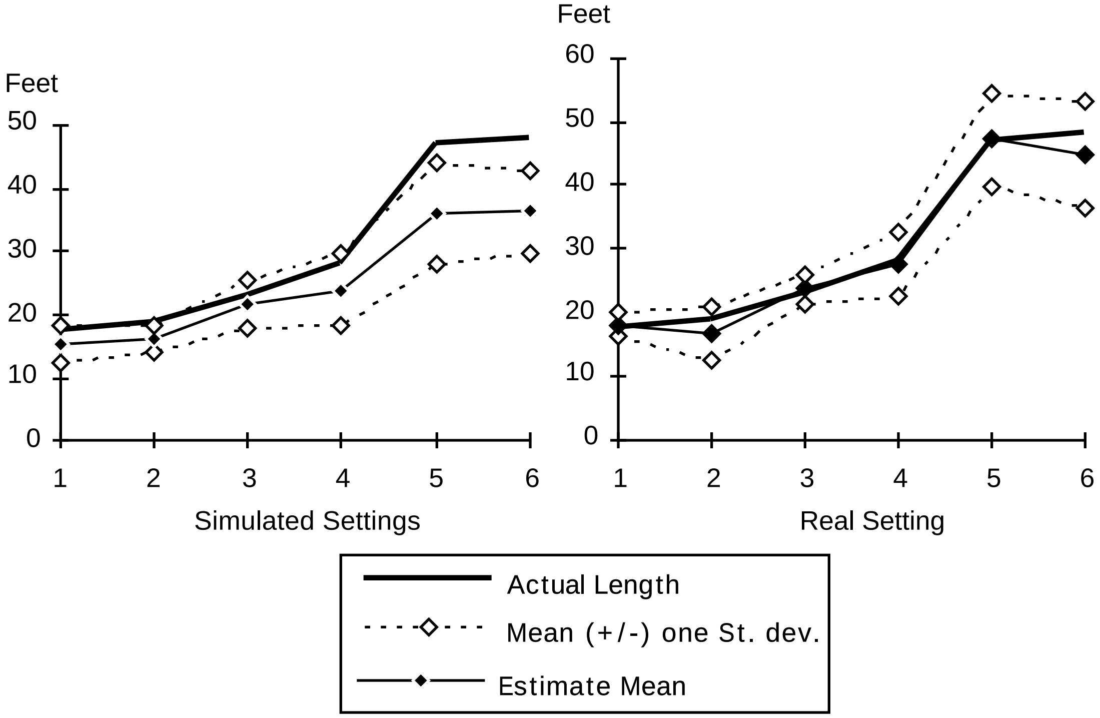


Fig. 7.1 - Actual area of rooms as a function of estimated area.

The combined means across all conditions suggest that participants usually underestimated the dimensions of the rooms. These underestimates were related to the size of the rooms. The underestimating increased as the size of spaces increased. The six actual horizontal dimensions of the three rooms in the museum are 17.5, 18.5, 23, 28, 47 and 48 feet, represented as numbering from 1 to 6 respectively (Fig. 7.1).

The height estimates behave quite differently. Participants' results were all close to the actual height and there is no apparent relationship to the actual size. Two of the room heights were 14 feet and one was 20 feet, represented as numbering from 1 to 3 respectively (Fig. 7.2).

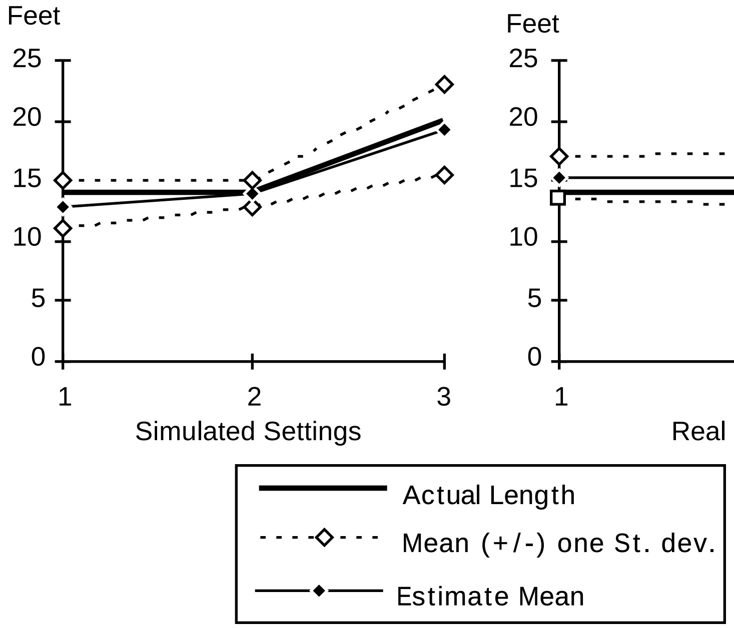


Fig. 7.2 - Actual height of rooms as a function of estimated height.

These general observations confirm the importance of distinguishing between vertical and horizontal distance estimates. The height overestimates also indicate that a particular architectural design can have the effect of making spaces feel taller, if desired.

Size Estimates - The Effect of Display in the Horizontal Dimension.

A multi-comparison one factor ANOVA for horizontal distance estimates shows a significant main effect due to display conditions with p<.0001 at the 95% confidence interval. The underestimates for dimensions in all of the simulation conditions are significantly different from the Real condition. Results for the Real display condition were quite accurate (Fig. 7.3).

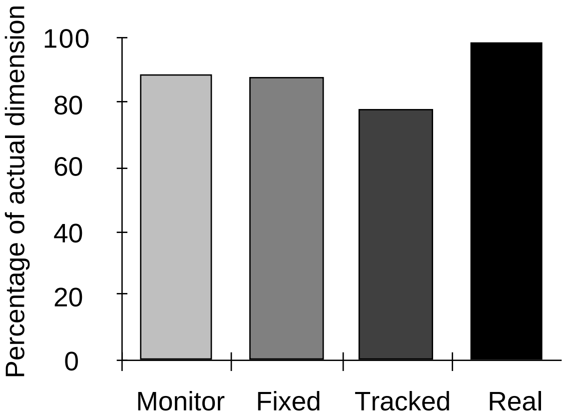


Fig. 7.3 - Average horizontal distance estimates of spaces in the four test conditions.

Among the simulation conditions, the underestimated values in the Tracked condition were significantly smaller than the other two display conditions, according to the Fisher PLSD test. Furthermore, the more conservative Scheffe F-test suggests that the Tracked condition was also significantly different from the Real condition (Table C.1 in Appendix C: Statistical Tables).

Size Estimates - The Effect of Display in the Vertical Dimension.

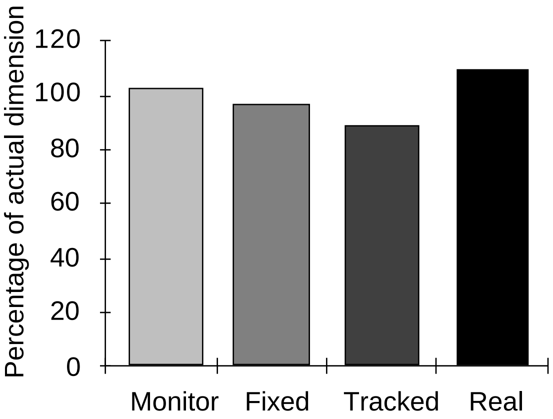


Fig. 7.4 - Average height estimates of spaces in the four test conditions.

A multi-comparison one-factor ANOVA for height estimates suggests there is a main effect between display types, with p<.0003 at 95% confidence interval. The means for the simulation conditions are all smaller than the Mean for the Real condition, as was the case for the Horizontal dimension (Fig. 7.4).

Both the less conservative Fisher PLSD test and the more conservative Scheffe F-test indicate that the Tracked condition results are significantly smaller than the Monitor and the Real condition. Both tests for individual differences also show that, in the two Eyephone conditions, Fixed and Tracked, the estimates were significantly smaller than in the Real condition (Table C.2 in Appendix C: Statistical Tables).

Size Estimates - Self-reported Ease and Confidence - General Observations.

In general, there was little variation in the self-reports for ease and confidence in doing the size estimation task (Fig. 7.5). Furthermore, people's standards for what constituted "easy" and "difficult" varied. For these reasons, the significance of this data is diminished.

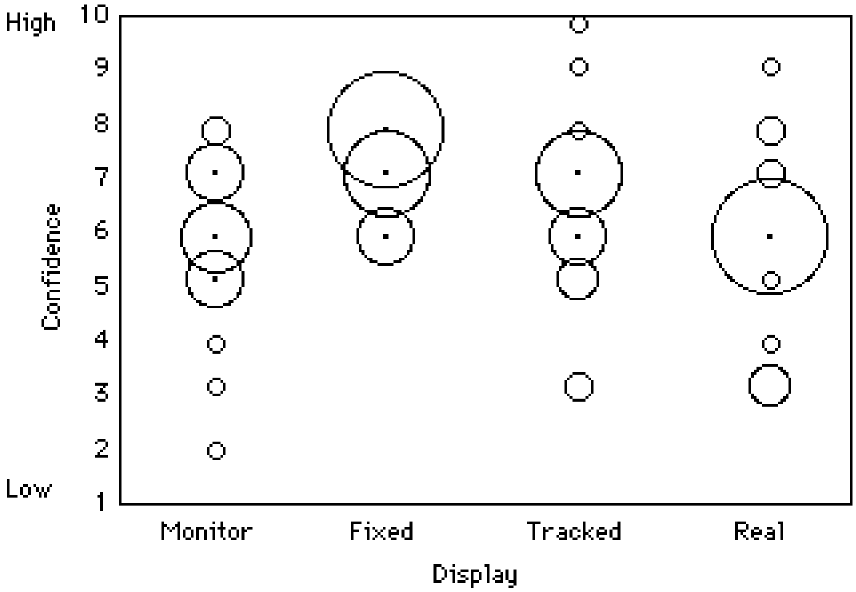


Fig. 7.5 - "Level of confidence" in the size task.

A one factor ANOVA for Ease has a main effect across display conditions with $p<0.003$ at the 95% confidence interval. According to the Fisher PLSD test, participants in the monitor and the fixed conditions felt their tasks were easier than participants in the Real condition (Table C.3 in Appendix C: Statistical Tables).

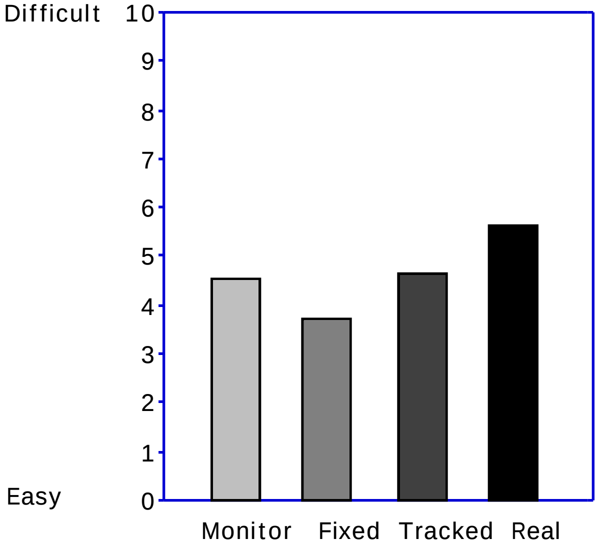


Fig. 7.6 - "Ease of estimating sizes" (Means).

Similar results were expressed for the confidence participants had in their estimates. There was a main effect for confidence with $p<0.02$ at the 95% confidence interval. Participants in the Fixed condition expressed more confidence in their values than those in the Monitor and Real conditions, according to the Fischer PLSD test (Fig. 7.6 and Table C.4 in Appendix C: Statistic Tables).

Size Estimate - Horizontal Dimension - Discussion.

All of the horizontal dimension estimates in the simulation conditions were significantly smaller than those in the Real condition. There are several possible explanations.

The model. Since the dimensions were underestimated in all of the simulation conditions, the results could suggest there was something inherent to the scale of the model which made the spaces appear smaller. However, this is not likely because the scale of model in the present system was calculated very accurately.

Movement. Another explanation is related to the difference in the way people moved through the spaces. As discussed earlier, the act of physically walking is a very important cue for getting a sense of rate of movement and distance. Participants in the real condition physically paced across the spaces. Participants in the simulation conditions had no kinesthetic feedback for their movement. Their rate of movement could only be perceived visually. There is little reason to believe however that simulated movement should necessarily make distances appear to be shorter. Furthermore, the participants were stationary while doing the distance estimates.

Field of View. With regard to the field of view, these findings concord with other studies which have shown that the perception of size and distances diminish as the field of view narrows (Dolezal 1982, Alfano 1990). This is better know as the size-constancy problem. The moon illusion is a well know example. The moon appears to be larger when it is close to the horizon than when it is directly above. Yet the moon does not really diminish in size. The field of view for both eyes was constrained to 90° in all the simulation conditions. More specifically, the peripheral vision was deprived of about 45° per eye. Although the 90° field of view is more generous than those in the Dolezal or the Alfano studies (explored the 60° to 12° field of view), it certainly seems to follow that trend.

Previous experience. Participants in the Real condition knew the space significantly better than the other participants (Please refer to Appendix B: Data Figures - Participant Profile). This might explain some of the differences between the simulation conditions and the Real condition.

Other factors. There are of course numerous other differences between the Real museum and the simulated one. People walking through the real museum could hear their footsteps. They could feel and smell the qualities of the air, and they probably perceived many other aspects to the space which did not exist in the simulation condition, and yet which played a role influenced their perceptions (see Canter 1977).

The Tracked condition estimates were also significantly different from both the Fixed and the Monitor simulation conditions. The head-tracking device differentiated both the Fixed and the Monitor condition from the Tracked condition. In the Tracked condition, participants turned their heads to change directions, whereas in the other two conditions, participants rotated the Spaceball.

Search pattern. The results suggest that source of difference between the non-tracked and the tracked conditions lies in the difference in the searching pattern. In the non-tracked conditions, participants wishing to see another portion of the space must rotate the model with the Spaceball. In this scenario, the participants trying to estimate the dimensions of a room are basically panning the images in front of their field of view until the edge of the room appears. This is a rather "passive" way to search the spaces.

The process of searching the spaces is more "active" in the Tracked condition. Users turn their heads (and bodies) in search of the room edges, much as they would in a real space. They are potentially better able to anticipate where the corners should be precisely because the position of their body is mapped one-to-one to the model. In that process, the gaze is engaged. While turning their eyes in the direction of the anticipated corner of the room, they end up seeing through the edges of the eyephones, precisely where the distortion of the optics is greatest.

<u>Tracked condition setup.</u> Another explanation might be related to the way participants interacted with the model. The space ball was fixed to the table in all three conditions. In the case of the Fixed or Monitor conditions, this was a convenience. However, it was much less appropriate to use in the Tracked condition. It was difficult for participants to use, especially when turning full circles. This might have affected the process by which they explored the spaces. In any event, it made the task awkward.

<u>Gender</u>. A note might be said about the gender distribution across the display conditions. At the same time, results suggest women underestimated room sizes more than men. There were many more women in the Tracked condition than in the other three conditions. Of the 24 subjects, 5 were women, and three of those experienced the Tracked condition. While their subject group was very small, it might explain at least in part why the scores were so much lower than the Fixed condition (Table C.5 in Appendix C: Statistics Tables).

<u>Size Estimate - Vertical Dimension - Discussion.</u>

As indicated earlier, the height estimates were greatly affected by the known standardization of building materials. While this improved people's estimates, it did so evenly across display conditions. All of the estimates in the simulation conditions were smaller than the Real condition estimates, as was the case for horizontal estimates. The explanations for the differences between the vertical dimension estimates in the Real and all three simulation conditions is probably the same as it was for the horizontal dimension.

When looking at individual differences between the display conditions, it was found that both stereoscopic conditions were significantly different from the Real condition. This further supports the conclusions about the underestimated horizontal results, which suggests that the limited field of view has the effect of diminishing people's perception of distances.

There is also a study which indicates that estimates of size and distance are more accurate in conditions where the peripheral vision has *at least some* visual stimulus, even if the stimulus has no direct relationship with the information in the fovea (Hagen 1978). Hagen conducted an estimating task comparing, among other things, the perception of size and distance in a real setting as viewed through a truncated window, with the perception of size and distance when seeing a slide view of the same scene. The field of view is identical in both instances. While not statistically significant, subjects did tend to underestimate distances and sizes more in the "truncated" view of the real scene than in the view of the slide. This suggests that the information in the periphery, in this case, the room where the projection was taking place, the seats and the walls, while entirely unrelated to the projected image, nonetheless served as a kind of context by which to better judge the sizes of objects in the fovea field of view.

Their study is similar to the Museum study. The Monitor condition is equivalent to the "slide" condition in the Hagen study, and the Eyephone conditions are equivalent to the "truncated view" of the real scene. Both the monocular and binocular conditions display the model 90° around the fovea. In the Eyephone conditions, the participant has no visual information in the periphery. They only see the black rubber of the device. In the Monitor condition, the participant can see the rest of the laboratory in their field of view. It serves as a context, or a frame of reference, much as the projection room did in the other study. The means between the Monitor and the Eyephone conditions do show that, like the Hagen study, the Monitor condition values were less underestimated.

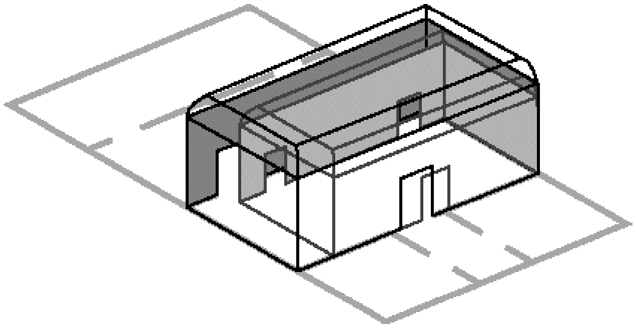


Fig. 7.7 - Schematic representation of perceived size in a virtual and real space. Perceived volume in Tracked condition (gray) and the Actual volume (black)

The significant underestimating which is perceived in virtual spaces is an important finding. If the values for the means of the three dimensions are multiplied, they would describe a volume of the main gallery of the museum to be 60% that of the actual size (Fig. 7.7).

The results for Ease and Confidence are not very reliable because they were self-reported values. They nonetheless indicate that it was easier to estimate the size of the volumes when viewing the simulations rather than when being in the real space. This is interesting because it would support the purpose of this representation. By being free of distractions and unnecessary details, representations make it easier for people to judge and evaluate specific spatial attributes, in this case, the dimensions of the spaces.

The Orientation Task - Analyzing the Data.

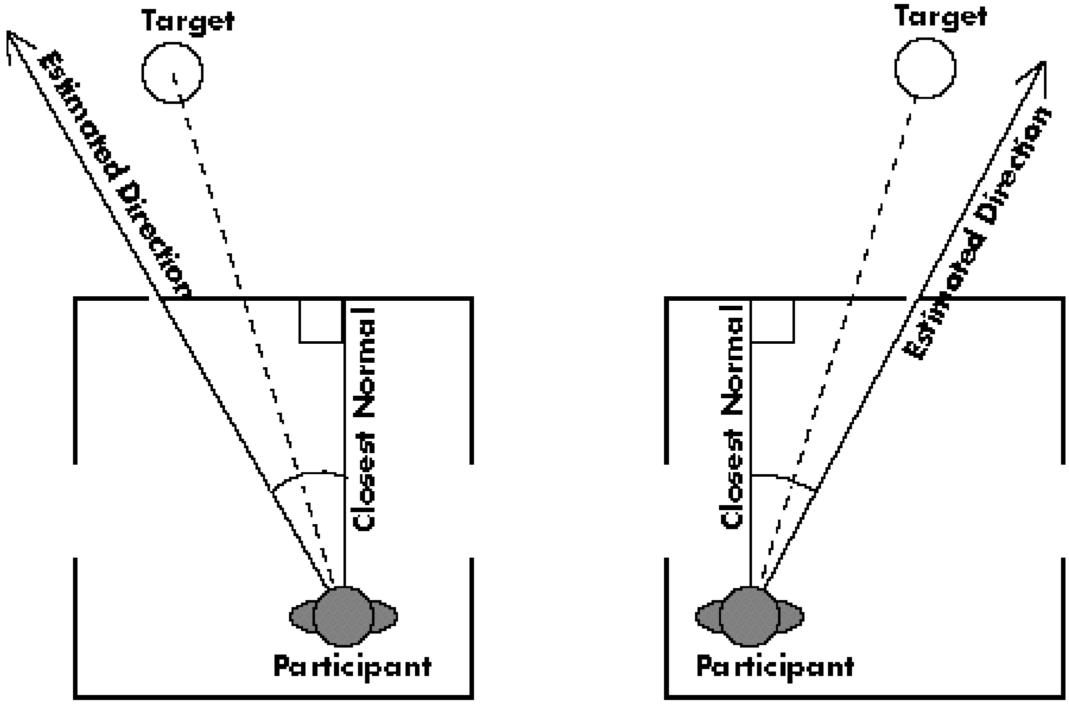
In the angle task, participants were asked to point to or face in the direction of three objects they had seen previously during their tour. Walls obstructed the target objects from view. As a result, the participant's task was to remember where the object was, and then to estimate its location.

In the Real condition, participants pointed in the selected direction with their hand. In all of the simulation conditions, rather than pointing, they were asked to center their view in the direction of the target.

The estimated angles were subtracted from the actual angle of the target. The data is therefore converted into "angle in error from actual target direction". Since the size of the target was quite large, and because the technique for expressing a desired direction was not extremely precise, it is assumed that differences under 5° are insignificant.

The Orientation Task - General Observation.

A first look at the data suggests that the values from the three target tasks need to be normalized before they can be averaged because they have a bias. Participants consistently overestimated the angle to the target in the same direction (Fig. 7.8).



Third pointing task:
Target left of Normal
results in overestimates
to the left

First and second pointing task:
Target right of Normal
results in overestimates
to the right

Fig. 7.8 - Bias in the angle task.

In the first two target conditions, the target is to the right of the closest normal (in geometric terms, the normal is the line which describes a perpendicular angle between the observer and a facing wall). In those conditions, participants across all four conditions estimated the target to be even farther to the right. In the third target condition, the position of the target is the mirror invert of the first two target tasks; it is to the left of the nearest normal to the facing wall. Subsequently, estimates were more to the left than the target. Biases are common to the pointing task. Generally, people are biased by the direction from which they have been traveling (Okabe 1986, Lindberg 1980).

A scattergram for the data points by target shows the two trends for the distribution of error (Fig. 7.9). Most of the estimates for the first and second angle are to the right (positive), and most of the estimates for the third angle are to the left (negative angles).

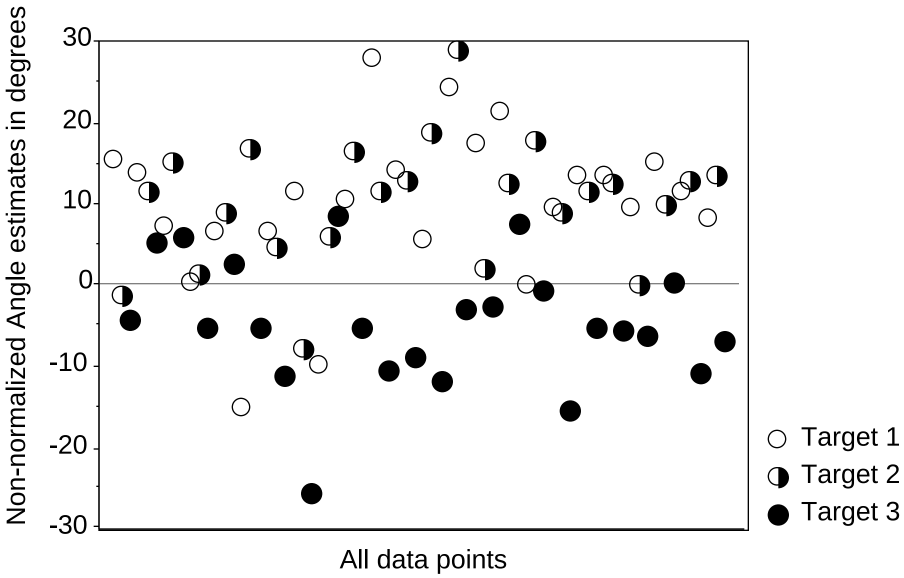


Fig. 7.9 - Distribution of angle data *before* it is normalized.

The data can be normalized by multiplying the values from the third angle by (-1). The scattergram illustrates this (Fig. 7.10). Positive values become overestimates in the direction of the target, relative to the closest normal, and negative values become underestimates.

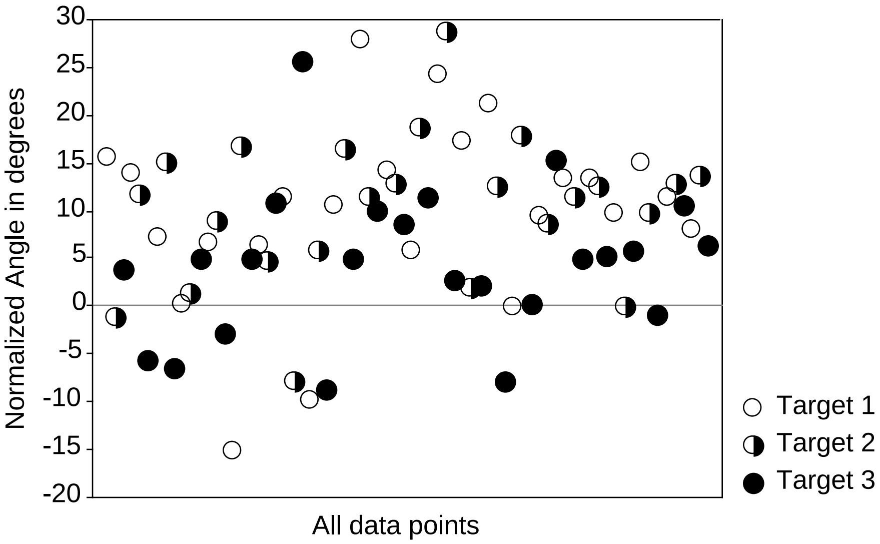


Fig. 7.10 - Distribution of angle data *after* it is normalized.

After the data is normalized, a one factor ANOVA suggests there is a significant difference between the three target estimates across all four conditions, $p<0.03$ at the 95% confidence interval. The Fisher PLSD test for individual differences shows that estimates for the third target were much better than the other two (Table C.6 in Appendix D: Statistics Tables). This might indicate that participants' cognitive map of the museum improved as their visit progressed. In any case, a 2 factor ANOVA for display and target versus the normalized angle shows no main effect for the interaction, p<0.65 at the 95% confidence interval (Table C.7 in Appendix D: Statistics Tables).

The Orientation Task - The Effect of Display

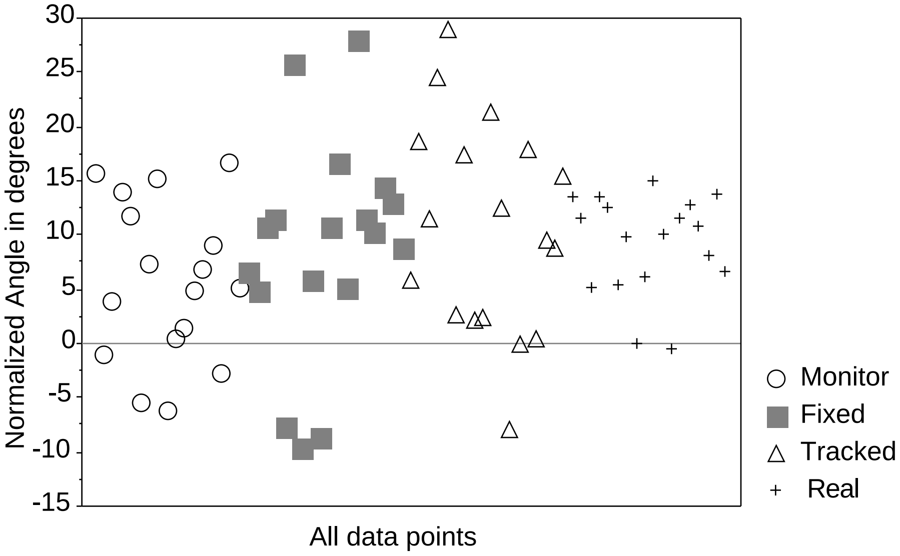


Fig. 7.11 - Distribution of normalized angle data.

A multi-comparison one factor ANOVA for the normalized angles shows no main effect for display condition, p < 0.17 at the 95% confidence interval (Table C.8 in Appendix C: Statistics Tables). However, when taking a look at the distribution of the data, certain trends become apparent. The diagram below shows the distribution of error by display type. While it is not clear that the *means* are different, the *variance* in the distribution of the data is on the other hand quite different. This trend was not signaled in the ANOVA statistical test because this test is sensitive to differences in *means*, rather than differences in *variance.* While the mean is an important measure, the success of the orientation task is just as much a function of the variance of the estimates. In the Real condition, the tightness of the distribution reflects a certain consistency across all the subjects, even though the angle scores were on average 9.2° off their target (Fig. 7.11).

In the simulation conditions, the distribution has a much greater variance. This could reflect a greater uncertainty in participants' task of estimating the direction to the targets. A *post hoc* ANOVA on the variance of the angles from the mean of each display condition suggest that there is a main effect at the 90% confidence interval, with p<0.07. The diagram is another representation of the means and standard deviations, by display condition (Fig. 7.12 and Table C.9 in Appendix C: Statistics Tables).

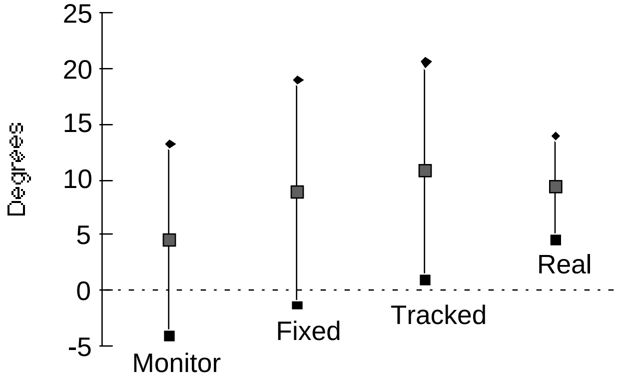


Fig. 7.12 - Means and standard deviations of angle data.

The Orientation Task - Self-reported Ease and Confidence.

Participants did not find the orientation task to be significantly easier in any one display condition. A one factor ANOVA shows no main effect, with p < 0.11 at the 95% confidence interval (Table C.10 in Appendix C: Statistics Tables).

There was no relationship between confidence participants had in their angle estimates and their display condition, p<0.49 at the 95% confidence interval (Table C.11 in Appendix C: Statistics Tables).

The Orientation Task - Discussion.

There was a general trend across all display conditions to overestimate the angle to the target by an average of 8°. This is common in orientation tasks and in cognitive maps in general. In similar studies, it has been shown that people's angle estimates can be biased by the path of their tour. Okabe has found that, "When a trail was winding and there were no landmarks along the trail, direction judgment was biased toward the direction of the vanishing point of a traversed trail."(Okabe 1986). Kevin Lynch was a pioneer in the use of sketches to study cognitive maps of places. He has many examples of how people systematically straighten curved lines (Lynch 1960, Canter 1977). But while this seems to be clearly a case of bias, the reason for the bias is beyond the scope of this study.

While there was no significant difference in angle estimates between the four display conditions, subsequent analysis confirmed to some extent (at 90% significance) that the variance in the estimates in the simulation conditions were significantly greater than in the Real condition. These results begin to reveal how difficult it is to situate oneself in the computer generated environments.

There are several reasons to believe that the little differences in variance mask big differences in people's sense of orientation. The first is due to the simplicity of the test space. The museum has a symmetrical plan. Two pairs of rooms are identical in size which are laid out symmetrically about the plan. The three non paired spaces are distinctly different spaces. The building footprint is the rectangle. All of these attributes of "rectalinearity" greatly simplify the orientation task.

Another factor which greatly simplified the orientation task is that the main gallery and the entrance hallway were visited twice. Studies have shown that "repeatedly viewing a spatial event increases the accuracy of the observer's spatial representation" (Allen 1978, Passini 1984). Both the simplicity of the test site and the repeated viewing of the spaces raise the expectancy in the accuracy of the estimates. Participants should be about as good as they will ever be. This means that little errors in angle estimates are really quite significant.

Normally, when evaluating the results of the orientation tasks, it is assumed that the chance expectancy is 90° because errors can range from 0° to 180°(Presson 1987). But because of the simplicity of this task, the chance expectancy is quite a bit lower. The combination of the rectangularity and symmetry of the space limited the possible range of errors from 0° to 45°, and therefore reduced the chance expectancy to 22.5°. In the context of this range, the simulation results were approaching randomness.

There are several possible explanations for the apparent randomness, or at least the lack of consistency in the estimates of the simulation conditions, when compared to the results of the Real condition:

Field of view. One of the differences between the Real condition and the three simulation conditions is size of the field of view. As discussed earlier (Chapter 4. Hypothesis), it has been shown that "the overlap of peripheral and fovea information is necessary for veridical perception to occur, … and that restricting the field of view will interfere with both perception and visuomotor performance " (Alfano 1990). Although these studies concern a field of view truncated to 60°, rather than the 90° in the eyephones, it remains nonetheless a plausible explanation for the imprecision in the estimates.

One of the other effects of having a limited field of view is that participants could not back up enough in the space to see as much of it as participants could in the Real condition. So while participants in the simulation conditions might have known quite well where the target was, their view of the space was too limited to express the direction accurately. It is very similar to the difficulties encountered when one tries to hang up a poster by oneself. Although one knows what looks straight and what does not, it is nonetheless difficult to place the poster because one does not see enough of the rest of the room in one's field of view.

As a result, it is unclear whether the limited field of view hampered people's ability to build a cognitive map, or whether it just made the task of identifying their selected direction difficult.

Movement. The other important difference between the simulation conditions and the Real condition is the way participants move through the spaces. Participants in the Real condition physically walked around the space, whereas in the simulation conditions, they experienced the illusion of movement without the kinesthetic feedback. This was probably a considerable disadvantage for making accurate estimates of direction because the distance traveled could only be interpreted from the visual modality.

There is also an important factor which might have tainted the results for the Tracked condition. The Spaceball was fixed to the table in all simulation conditions (Appendix D: Interface Hardware). While this was appropriate for the non-tracked conditions, it served as an important indication of (dis)orientation in the Tracked condition. Since the orientation of the virtual space is mapped onto that of the laboratory space, participants had a constant kinesthetic cue as to the direction they were facing. The Spaceball would have been stripped of its role as an "anchor" to the participant's sense of orientation if they had been obliged to carry it with them. This would most probably have lead to different results.

Descriptive Questionnaire - Analyzing the Data.

The qualitative questionnaire required participants to rate the qualities of the main gallery space, using an adjective checklist. There were 13 bi-polar adjectives to choose from (see Appendix A: Questionnaire). The purpose of this task was to look for resemblance in the overall spatial description of the gallery, rather than to study specific differences in attributes of the space.

Descriptive Questionnaire - General Observation.

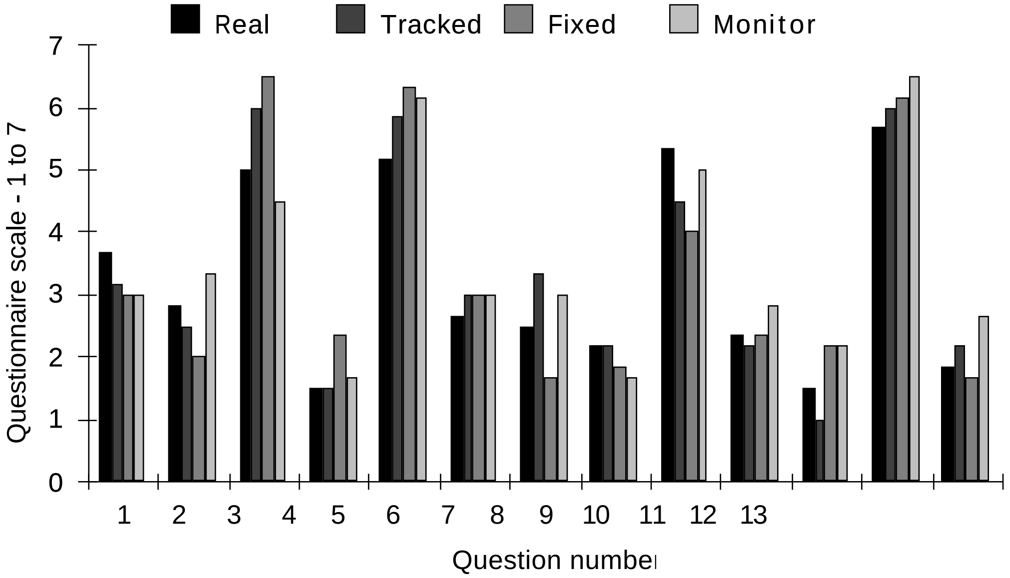


Fig. 7.13 - Descriptive task averages by question number.

There appears to be a remarkable similarity in the results across display conditions (Fig. 7.13).

Descriptive Questionnaire - The Effect of Display.

Because the adjectives are non-parametric, each question is measured separately across the four display conditions. 13 one-factor ANOVAs were run, one for each question. There were only significant differences between display conditions in question 2 and 3. Question 2 had a $p<.02$ and question 3 had a $p<.007$ at 95% confidence (Table C.12 and Table 13 in Appendix C: Statistic Tables).

In order to properly compare these non-parametric results as a whole, a simple regression was computed (Table 7.1). The graph below summarizes the findings.

Table 7.1 - Descriptive task regressions results.

	Monitor	Fixed	Tracked
Fixed	.74		
Tracked	.83	.84	
Real	.88	.79	.91

Regression values (r^2)

The greatest correlation is between the Tracked condition and the Real condition. The Monitor and the Real condition also had a high correlation. The Fixed condition was perhaps the only one to be somewhat different from the others, although a $r^2=.79$ is a rather high correlation.

There exist no absolute values which describe the qualities of interior spaces. Instead, the "objective" attributes are based on the average of many people's perception of the space. If this is the case then, the goodness of the simulations can be measured as a function of the distance of these scores from the Mean of the Real condition scores for each question. A *post hoc* analysis suggests, although not at a statistically significant level, the Tracked condition results were on average much closer to the Real condition than the other two simulation conditions (Fig. 7.14).

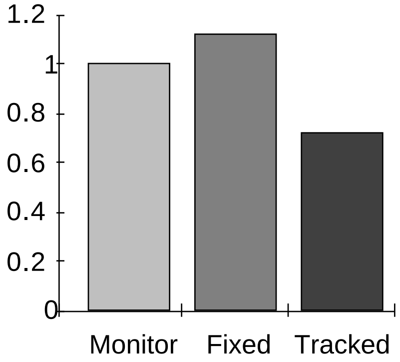


Fig. 7.14 - Average difference in variation from the mean of the Real condition (based on the 1 to 7 semantic differential scale).

Descriptive Questionnaire - Discussion.

The results from the adjective checklist are all relatively similar. However, the comparison between the difference of the values in the simulation conditions and those from the control group (Real condition), indicate a greater concordance between the Real condition and the Tracked condition than with the other two simulation conditions. This would seem to confirm that people are better able to judge the feel of models in virtual environments than in walkthroughs. In a sense, these conclusions are to be expected because it is much easier to judge the feel of a space when one is *present in it* than when one *looks at it*. Of all the simulation conditions, the Tracked condition the most effective at creating the illusion of presence.

The concept of having a "sense of presence" in a computer model comes "hand in hand" with the invention of virtual interfaces. Magazines about virtual interfaces are even entitled "Presence". In fact, the sense of presence is so much greater in virtual environments than when viewing walkthroughs, that it is surprising to not find a greater difference.

Perhaps the lack of greater difference between the Tracked condition and the other two conditions is due to the simplicity of the test space. As a museum space, the main gallery was purposefully neutral and free of unnecessary details. There was a limited number of attributes to describe it. Furthermore, the list of attributes in the questionnaire was much shorter than its author intended (see Chapter 3). The combination of these two factors might explain the relative similitude in participants' perception of the space across the various display conditions.

Additional Questionnaire Results.

In addition to the results above, participants were asked to perform other less easily quantifiable tasks. The purpose of these tasks was to explore and probe for other unknown possible differences between the display conditions. These include a sketch task, questions about participants' most and least favored spaces, as well as open ended questions about the interface they experienced.

Sketches Task.

After their visit, participants were asked to draw the plan of the gallery. Their plans were rated as a function of their perception of (1) the location of rooms relative to each other, (2) the path of visit and (3) their ability to rank the spaces by size from smallest to largest. This less formal task was designed to capture information which might not have been apparent through the size and angle tasks.

The maps are loosely rated as a function of the number of errors made. The scale is the following; 0 errors = 100%, 1 error = 50% and 2 or more errors = 0%. For example, if a participant forgot to draw one of the rooms, their sketch would have a score of 50%.

Sketches Task - Cognition Map Accuracy.

In general, the maps were all quite accurate. This is to be expected, given the simplicity of the test site.

1. Relative location of rooms: Participants in the Real and Tracked conditions had a perfect sense for the relative location of spaces. Some participants in the Monitor and Fixed conditions had a much less clear cognitive map of the gallery spaces (Fig. 7.15).

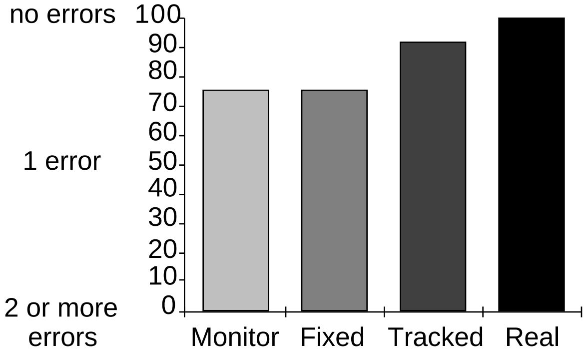


Fig. 7.15 - Accuracy in recalling the relative location of spaces.

2. Path of Visit: Participants in the Real condition had a perfect recollection of their movements through the gallery. The simulation participants had more difficulties doing this task (Fig. 7.16).

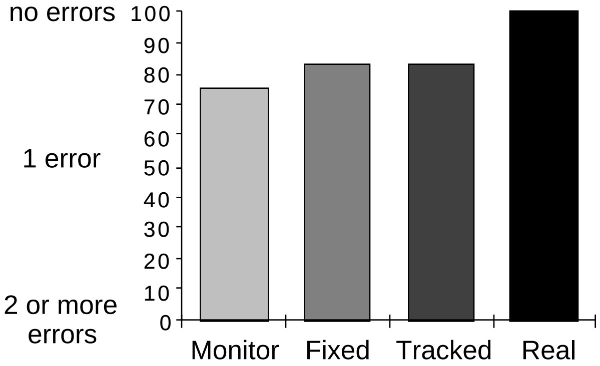


Fig. 7.16 - Accuracy in recalling path of visit.

3. Relative Sizes Volumes: Participants had problems distinguishing the size of the two small paired rooms, A & C and E & F (for a plan view, see Fig. 6.3). Some participants did not even recognize that the small rooms were identical in size. The task was as difficult for three of the four conditions. Participants in the Fixed condition fared much worse (Fig. 7.17).

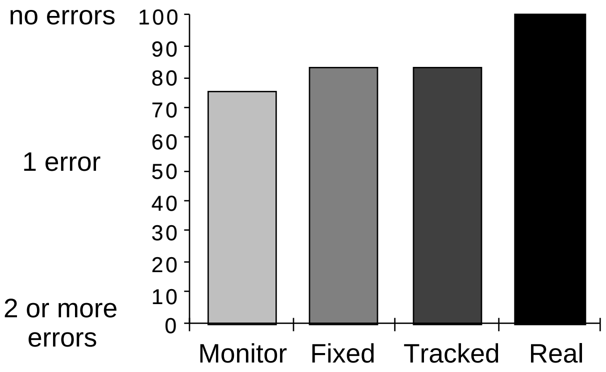


Fig. 7.17 - Accuracy in ordering spaces by volume size.

Overall, results from the sketch task suggest that participants in all four conditions had a rather accurate cognitive map of the museum. However, the average accuracy of the three sketch tasks indicate that the participants in the Tracked condition might have been better able to build an accurate cognitive map of the spaces than those in the other two simulation conditions (Fig. 7.15, 7.16 and 7.17). If that were the case, it would further emphasize the fact that the pointing task was not effective in measuring the accuracy of people's cognitive maps.

Sketches Task - Subjective Evaluations.

The second portion of this task consisted in comparing general subjective views about the gallery as a whole. Participants were asked to rate which space was (1) easiest to size-up, (2) the most pleasant and (3) the least pleasant. They were asked to explain their answers. What quickly becomes apparent when looking at the data is the tremendous variability due to the differences in the participants. What makes a space pleasant for one person only partly applies to the next. As a result, the effect of the environment is difficult to distinguish.

1. Easiest space to size-up: Most participants agreed that either the first small rooms "A" and "C" were the easiest to size up or the main gallery space "D" (Fig. 7.18). The small ones were easy because participants could see more of the walls without distortion, and their human scale helped them judge distances. Those who felt the larger room was easier usually said it was because of the scale figures.

Some suggested that spaces which were visited more than once became familiar and therefore easier to size up. Both "D" and "C" fit this category (for a plan view, see Fig. 6.3).

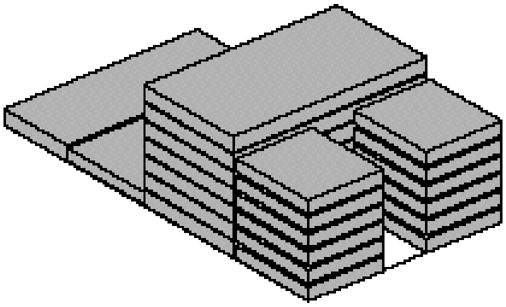


Fig. 7.18 - Easiest rooms to "size-up".

In the Monitor condition, the task of sizing up spaces was judged easiest in rooms which required no panning, which included scale figures, or which were small.

Participants in the Fixed condition felt that, as in the Monitor condition, distortions due to panning of spaces made the task difficult. They also preferred spaces with a scale figure. What is new about this group is the effect of adaptation. They, more than any in any other condition, expressed a need to adapt to the simulation model. They found it easier to size up rooms which they had visited multiple times, or after they had felt more comfortable with the experience.

In the Tracked condition, participants found small spaces to be easiest to size-up.

Like the other conditions, Real condition participants felt that the size of the room affected the ease of the sizing task. But unlike the simulation conditions, participants did not feel as great a need for scale figures. Instead many expressed they could use themselves as scale figures.

2. Most pleasant space: 70% to 80% of the participants across all conditions preferred the large main gallery space. People who liked cozy spaces preferred room "A". Those who liked more open spaces preferred the main gallery space "D" (for a plan view, see Fig. 6.3).

3 The least pleasant space: There was no general agreement as to which space was most unpleasant (diagram F). Real condition participants did not like the end space "G" much.

The participants in the simulation condition did not get exactly the same introduction to the hallway "B" and certainly did not get to appreciate the detail it actually contains, and it was therefore often mentioned as an unpleasant space. But most participants agreed that spaces where unpleasant either because they were movement spaces rather than pause spaces, or because of the proportions of the room.

(For a more complete decomposition of the results for the sketch task, please refer to Appendix B: Data Figures - Sketches)

General Experience with Interface - Wayfinding and Presence.

In an attempt to further explore participants' cognitive maps, they were asked to judge whether or not they got lost during the tour, the number of times this happened, and how that affected their sense of well being. None of these questions delivered statistical findings (refer to Appendix B: Data Figures - General Experience Evaluation).

Interface Evaluation - General Observation.

These are self-reported open-ended questions about the simulation interfaces. The purpose of these questions was to (1) look for the main factors which participants felt influenced their ability to do the tasks and (2) to identify and prioritize the aspects of virtual interface technologies which require most urgent improvements.

Participants listed 3 things about the experiment that made their task difficult, and 3 things which would make their task easier. The answers were clustered after the study was conducted and divided into 4 main categories: Procedural, Model, Interaction and Input Device.

Architects overall felt that both the input device and the rendering of the model were the most important factors in helping or hindering their tasks during the experiment (Fig. 7.20). They felt the tasks would have been easier if there had been more cues about the scale of the space, such as scale figures and texture mapping. Many found the Spaceball difficult to use. Many participants also complained about the low resolution of the eyephones and their limited field of view (a complete breakdown of these evaluations is located in Appendix B: Data Figures - Participant evaluation of interface).

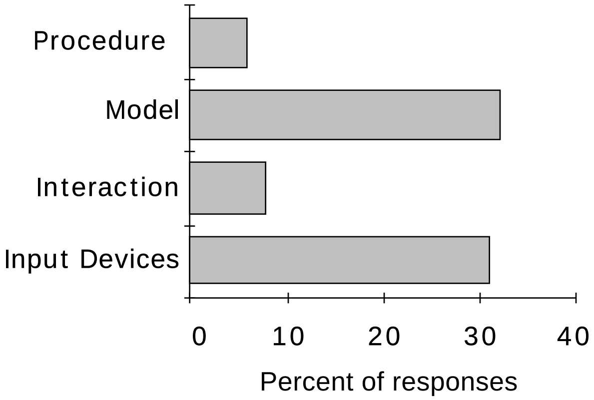


Fig. 7.20 - Aspects of experiment that made the tasks difficult.

Interface Evaluation - Professional Uses of Interface.

Participants were asked to rate the simulation techniques for making design decisions in several specific situations: during a public hearing, specifically to make evaluations about volumes and transitions between spaces, for positioning artwork and for placing furniture (Fig. 7.21).

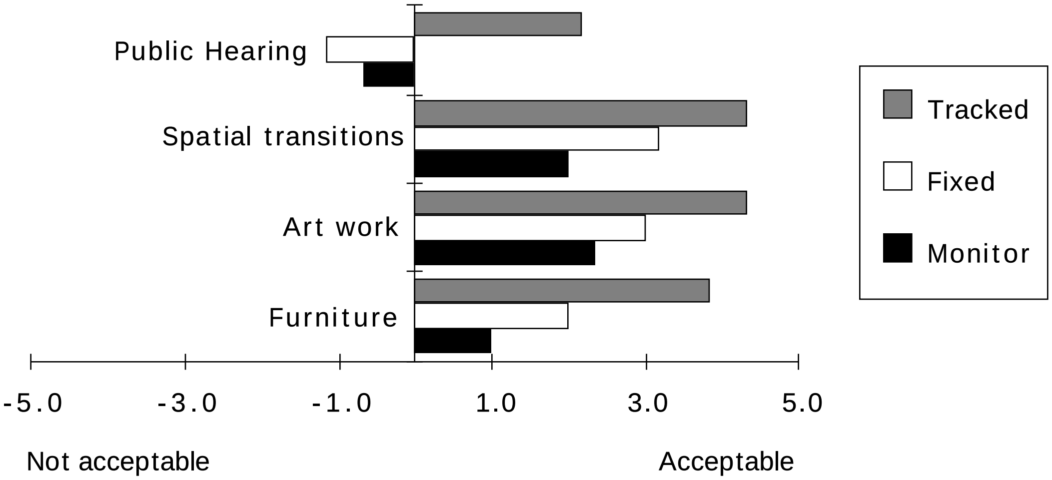


Fig. 7.21 - Professional acceptability of the display conditions.

There is no significant difference in the rated "acceptability" of the simulation tools. There is however a trend which suggest that users of the Tracked interface found the tool better suited for all the hypothetical uses.

Part of the better acceptability of the Tracked interface can be attributed to the novelty of the tool. But part as well can be attributed to how easy, intuitive and even enjoyable it is to use. Unofficially, I found that many participants in the Tracked condition wanted to continue to discover the museum even after the experiment was finished. This cannot be said for any participants in the other simulation conditions.

All of the simulation conditions were judged less professionally acceptable for public hearings than for the other three hypothetical uses. This might be due to the fact that only a few people can use the system at one time.

Participant Profiles.

As Bosselman suggests, their are several factors beyond the attributes of a space that affect people's perception. Five sets of variables have been identified as integral to investigations of environmental perception (Bosselman 1987):

> (1) characteristics of the observers (attitudes, professional training), (2) medium selected for presenting the settings, (3) the response formats used and the range of reactions they encompass, (4) the environmental attributes of the settings and (5) the nature of transaction with the setting, prior familiarity.

The first (1) and the last (5) variables are recorded in the participant profile. An unequal distribution of participant profile could complicate the task of analyzing the data.

1. Characteristics of the observer: Participants were asked their occupation, age, and their gender. I assumed that these were the predominant characteristics which might have implications on the results. All were in the architecture profession, except for one subject (whose results were thrown out). There was no significant difference for age; most were in the 25 to 34 age group. Their was a significant difference in the distribution of women subjects. There were 5 women out of 24 participants, and 3 of them experienced the Tracked condition. Further analysis suggested women underestimated sizes significantly more than men. The effects of this are mentioned in the discussion of the Size task.

2. The Nature of the Transaction with the Setting, prior Familiarity: It was a genuine concern that users who knew the space well would be able to respond to the simulation task by relying on their memory of the real space. To guard against this, participants were asked questions pertaining to their previous experience with the Henry Art Gallery. There were asked if they had ever been there, how long ago, how many times, and then they

were asked to self evaluate how well they felt they knew the museum. This became a measure of "memory" of the museum. As it turns out, the distribution of the participants showed no significant difference across display conditions, p<0.12 at the 95% confidence interval.

Participants were also compared for their previous experience with computers. This could have affected how comfortable they became with the various tools. It might have also affected their expectations with regard to virtual interface technologies. They were asked to rate their experience playing with video games, their experience using other simulation tools or architecture computer visualization software. There was an even distribution of previous experience with these tools across display conditions.

CHAPTER 8. CONCLUSIONS.

Perception of Distances - Conclusions.

A significant size task finding in this study is the extent to which distances are perceived to be smaller in the simulated environments. The horizontal and vertical dimensions of spaces in the simulation conditions were all perceived to be significantly smaller than in the real spaces. It would appear that this misperception is due to the well documented size-constancy phenomenon, whereby sizes and distances appear to be smaller when seen through a truncated field of view (Dolezal 1982, Alfano 1990).

The results also indicate that perceived distances are underestimated by a larger amount in the virtual environment than in both the monoscopic and stereoscopic walkthrough types of representations. These findings would tend to suggest that head-position tracking somehow affects the process by which people visual search the display in such a way as to diminish their perception of distances. Perhaps, when people are head-tracked, they tend to gaze more often at the edges of eyephones, in which case they would be more affected by the distortion in the eyephones than if they focused their gaze in the center of the optics.

Implications of the Distance Estimate Conclusions.

The underestimating of distances in virtual environments is large enough to raise concern about the uses of the tool in its present configuration for doing distance evaluations. Virtual environments, if used with a display configuration similar to the one in this study, could lead users to make considerable errors in judgments of volume size.

There are however several short term solutions to this problem. Since the underestimation of distance is consistently around 20%, users could use this information as a reminder to correct their initial perceptions of volume sizes. Another safeguard would be to include many familiar elements of scale in the model. Many participants indicated that the task would have been easier had there been more elements of scale (Appendix B: Data Figures).

A more durable solution for decreasing the effect of the size-constancy illusion would be to increase the display's field of view. At present unfortunately, it is very difficult and expensive to increase substantially the field of view in a eyephone display. It is a technology which to this day can only be afforded by the military.

Retro-projection is however another technique for presenting virtual environments which does not involve using the eyephones and yet which offers a large field of view. In this configuration, the participant stands in front of very large screens. The images are projected from behind the screen. As the number of screens increase, so does the field of view and the sense of immersion. One of the drawbacks of this configuration is that it is much more cumbersome than when using Head Mounted Displays.

An example of this display was demonstrated in the Virtual Building Walkthrough project at the University of North Carolina. In this set-up, participants looked at a very big screen projected by a Barcodata system (Brooks 1986). A more recent example is "The Cave" which was presented at the SIGGRAPH '92 exposition. It is a virtual environment in which the big screens completely surround the participant. In this scenario, the virtual model is displayed to the participant's entire visual field of view, just as it is in the eyephones.

At least some of the underestimating of distances must have been related to head-position tracking because estimates in this condition were slightly worse than in the non-tracked stereoscopic condition. Explanations for this effect could be the result of a relatively complex process and there is, unfortunately, no short term solution. It is clearly an area which will require further research.

Perception of Orientation - Conclusions

While none of the results for the orientation task are statistically significant, they do indicate that participants viewing the simulations were fairly less precise in their angle estimates than those in the real museum. If however, the relative simplicity of the task is taken into consideration, then even a small difference in the degree of variation between the Real and the simulated conditions would confirm the difficulty people have in building an accurate cognitive map of simulated environments.

There are several reasons to believe that this is the case. First of all, it would agree with the numerous observations at the H.I.T.Lab in which people were lost and confused about their orientation when in virtual environments. It would also coincide well with the many projects[1] at the lab which where instigated out of a concern for this problem.

There is evidence that the limited field of view in the displays could disrupt people's ability to build a good cognitive map and therefore reduce their accuracy in the pointing task. As previously quoted in Chapter 7, "the overlap of peripheral and fovea information is necessary for veridical perception to occur, … and that restricting the field of view will interfere with both perception and visuomotor performance " (Alfano 1990). If that is the case, it could explain why it is so difficult to know where one is in a virtual environment. The exploration of the effect of varying the field of view on cognitive mapping tasks is yet another instance where further research is required.

One more reason to believe that people had difficulties building a cognitive map of the spaces is the fact that they had no kinesthetic feedback to concord with the visual illusion of movement. In this respect, these participants were missing what might be an essential interaction for "understanding" the space; that of pacing the space to get a physical sense for its size along with the visual spatial information. It would be interesting to compare the H.M.D configuration to the configuration at U.N.C in which people move their viewpoint by physically walking. It would then be possible to determine the extent to which the physical feedback of walking helps in building a cognitive map of an environment.

Unfortunately, the study was conducted in such a way that makes it difficult to establish whether the imprecision of the estimates in the simulation conditions are due to people's inability to build an accurate cognitive map of the spaces, or whether it was impossible to do the task accurately even with an accurate cognitive map. The limited field of view of the displays implied that people had very little spatial information with which to base their orientation, even when they were guided to the corners in the rooms.

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[1] PolhemuStudy and GlobalView are both mini projects I worked on at the laboratory which addressed the problem of self-orientation (Unpublished technical write-ups).

Implications for the Perception of Orientation Conclusions.

In any event, regardless of the many valid concerns about orientation in virtual environments, the pointing task in the study did not reveal any conclusive differences either between the simulations and the real museum, nor among the simulations themselves. However, this does not imply that orientation is not a problem in virtual environments. Results from the informal sketch task vary in accuracy across the four display conditions, suggesting that there were differences to be measured in the pointing task.

One implications from these conclusions is the need to develop better methods for measuring people's sense of orientation in virtual environments. The model used for this study was too simple and the path of the visit was too informative. It was also ill-adapted for the display conditions in which participants had a limited field of view. Perhaps a completely different task is required, one which would require participants to actually find their way to designated target destinations.

Until further research can be conducted, architects wishing to use this tool could limit the problem of spatial orientation in virtual environments by providing the participant with additional layout information, such as a plan view of the space. This would enable users to correct and update their cognitive map of the spaces.

There have also been attempts to include additional information within the environments. One such project was for the design of a fighter cockpit virtual display. Along with a virtual representation of the landscape environment, the pilots were to be provided with a miniature view of their plane as seen from above. The miniature plan view is just one of many solutions which could help users to always know where they are.

Perception of the Qualities Spaces - Conclusion.

Overall, the results indicate that all the simulation conditions were successful at representing the general feel of the spaces. However, under closer inspection, results from the Tracked condition indicate that it was slightly more effective at representing the "feel" of the spaces than the other displays conditions. While not statistically significant, it does suggest the head-tracking device, combined with the stereo eyephones, enables participants to make accurate evaluations about the way a place "feels".

This is probably due to the fact that people feel as if they are really inside the model. Every motion of their head reenforces the illusion of presence in the virtual space. Feeling one is present in a space seems essential to being able to properly qualify it. This would explain why, on average, participants' qualification of the space in the Tracked condition was closer to the Real condition than were the other two simulation conditions.

Although virtual environments were expected to be more effective than walkthroughs for communicating the qualities of spaces, their actual difference in the study was not statistically significant. One possible explanation for the lack of greater distinction between the two conditions is that the test space was relatively simple. As a museum space, it was not designed to have a lot of character. The results were also potentially diluted during the process of selecting adjectives because I included only those which could appropriately define the space, thereby narrowing the variability in the responses.

Implications for the Perception of the Qualities of Spaces.

Results from the description task begin to demonstrate one of the specific advantages of using virtual interfaces to represent architectural spaces; that of being able to accurately assess how a place would feel, and conversely, how one would feel in a place. The tool, as it exists in this study, is at least as effective if not more so than the walkthroughs for conveying how a place would feel.

Overall Conclusion.

As measured with the three perceptual tasks, it becomes apparent that virtual environments do not fully satisfy the requirements for completely replacing those forms of architectural representations which are meant to convey the basic spatial characteristics of proposed spaces. The virtual interface used in this study is not quite good enough for making *quantitative* judgments of spaces. It is difficult to orient oneself in virtual spaces and distances are underestimated. However, the interface is adequate for making *qualitative* evaluations of architectural spaces. Using this interface, people's perception for the way the modeled spaces feel would rather accurately predict their perception of the feel of the real space.

In part , the difficulty of making accurate quantitative judgments is due to the narrowness of the field of view. These difficulties can be reduced if the horizontal field of view of the eyephones is increased or if a display technology using a wider field of view is used. The source of other problems are more complex; the effect head-position tracking has on the estimates is one example, and the lack of kinesthetic feedback for movement is another. Both of these areas would require further research.

While the type of virtual interfaces in this study are not adequate for quantitative tasks, they could be used to supplement other existing forms of architectural representations which are perhaps more effective at conveying the quantitative attributes of spaces but less effective at conveying how the spaces would feel. Typically, designers could continue to use drawings to convey the size and location of spaces while supplementing these with a virtual environment for conveying how the spaces would feel.

Another reason for supplementing existing techniques of spatial representation with virtual environments is that they are very easy to use. Interpreting spatial information using virtual interfaces is perhaps as simple and intuitive as it is to interpret real spaces. To interact with the virtual environment, participants used their body and head to look around as they would have in real spaces. This was certainly much easier than trying to interact with the walkthrough representation. Participants complained extensively about the movement metaphor in the walkthrough condition (see Appendix B: Data Figures - Participant Evaluation of Interface).

Similarly, virtual interfaces seemed to be more enjoyable to use than the walkthroughs. Many participants in the Tracked condition wanted to continue viewing the museum even after the tour ended. This could not be said of participants in the walkthrough type conditions. Perhaps this is also why the virtual interface was judged to be more professionally acceptable in many hypothetical instances. In any event, the appeal of the interface and its ease of use are its own very important distinctions. They confirm the significance of this technology and endorse continued research.

Future Research.

This study yielded conclusive results indicating that the limited field of view in the simulation conditions affected people's ability to judge distances accurately. Preliminary results also indicated that the restricted field of view and the lack of kinesthetic feedback might explain why it is so difficult for people to understand their orientation in the virtual environments. All of these difficulties were also found to be compounded by head-position tracking. To clarify these findings, the following areas of research would be required.

Studying effect of limiting the field of view in the periphery on:

- people's ability to build cognitive maps
- the perception of sizes and distances

Studying the effect of the head-position tracking on:

- the process of visually searching the display
- people's ability to build cognitive maps

Studying the effect of kinesthetic feedback for walking on:

- people's ability to build cognitive maps
- the perception of sizes and distances

There were also several instances where the results from the study were inconclusive. Some of the methods of measurement were either inappropriate or they were improperly conducted. The following areas could benefit from a re-investigation:

- using an alternative method for measuring people's understanding of the spaces

- using the complete adjective checklist in the qualitative study

Another area of research is comparing the use of an interaction device which is "anchored" to the physical space (as the Spaceball was the case in this study) to the use of the same device when held in the participant's hand, and the effect this has on:

- the process of visually searching the display
- people's ability to build cognitive maps

Extended Areas of Future Research

There are many other distinctive aspects of virtual environments which could affect the way people perceive spaces. Some of these characteristics could be exploited if they were found to improve users' spatial perceptions. Some of the sample topics are the following:

Exploring the effect of penetrable/impenetrable surfaces on:

- people's ability to build cognitive maps
- people's subsequent interaction with the real space

Exploring the effect of non-constrained vertical movement on:

- people's ability to build cognitive maps
- people's subsequent interaction with the real space

Exploring the effect of being able to render surfaces transparent on:

- people's ability to build cognitive maps.

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APPENDIX A. QUESTIONNAIRE

Part A. Orientation and Dimensions Tasks

Easy	1	2	3	4	5	5	6	7	8	9	10	Difficult
Total guess	1	2	3	4	5	5	6	7	8	9	10	Highly condident (within 1 foot)

1. Room "A"	**2. Room "G"**	**4. Room "D"**	**6. Room "C"**
Width :__________	Width :___________	Width :_____________	
Length :__________	Length :__________	Length :____________	
Height :__________	Height :__________	Height :____________	
Difficulty :___________	Difficulty :__________	Difficulty :__________	
Confidence (1-10) :____	Confidence :________	Confidence :_________	
	3. Deg. to "A" :	**5.** Deg. to "F" :	**6.** Deg. "E" :
	1st pt :____________	1st pt :___________	1st pt :_______
	2nd pt :___________	2nd pt :__________	2nd pt :________
	Ft. to normal :_______	Ft. to normal :_____	Ft. to normal :___
	Difficulty :__________	Difficulty :_________	Difficulty :______
	Confidence (1-10) :__	Confidence :______	Confidence :___

Walls times :
Lost times :
Comments :

As you enter the site, you will be asked to formulate your "first impressions" of the volumes. Your answers will be recorded with the aid of a small microphone. You may qualify your impressions and add to them as you proceed, until you have visited the entire place. You may talk about any aspect you wish.

An observer will prompt you with the following questions:

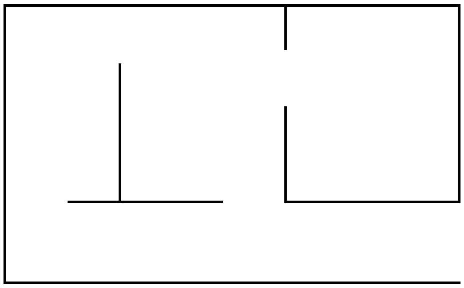
What are your first impression of the volumes?

What does it remind you of?

How does it feel; is it pleasant or unpleasant?

Part B - Recall of Relative Spatial Dimensions

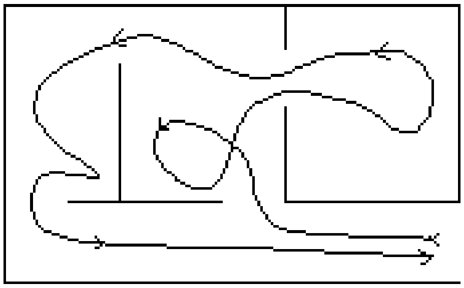
After having completed your visit, you will be asked to draw a map of the space as you remember it. Follow the instructions below.



Example of map.

1- Use the next page to draw a map of the place you visited (example above). The precision of your map is not important. It is a memory guide to help you answer questions later on in the study. Do not spend too much time on this task.

2- Use your plan to draw a line showing the path of your visit through the spaces. Place little arrows on the line to indicate the direction of movement (see diagram below).



2- Example of path. The path of visit is a thin curved line with arrows indicating direction of visit.

Plan view of the space
(A square was provided here for the sketch of the museum)

3. If "Volume" is the total area of a space as defined by its length, width and heigth, then rate each space from the smallest volume to the largest one. Attribute a 1 to the smallest, a 2 to the next largest and so on. If two spaces are the same size in volume, give each one the same value. Label those volumes directly on your plan.

4. Are there any spaces which were easier to "size-up" than others (label them "EASY" on the plan)? If so, explain why? (explain briefly)

5. Label the plan above with the letter "A" for the space which was most pleasant.
Why was it the most pleasant space? (explain briefly)

6. Label the plan above with the letter "F" for the space which was least pleasant.
Why was it the least pleasant space? (explain briefly)

Part C - Description of Volume

The following questions are presented as a set of opposite adjectives and are meant to capture your perception of <u>largest</u> room indicated during the tour. Simply <u>circle the number</u> on the 1 to 7 scale which best qualifies how you perceived that space. If you feel the type of tour you took gave you insufficient information to answer a particular question, circle the option "Can't say".

Ex. The space was …
Run down 1 2 3 4 5 6 7 New Can't say

1. The space was …
Cheerful 1 2 3 4 5 6 7 Gloomy Can't say

2. The space was …
Comfortable 1 2 3 4 5 6 7 Uncomfortable Can't say

3. The space was …
Complex 1 2 3 4 5 6 7 Simple Can't say

4. The space was …
Large 1 2 3 4 5 6 7 SmallCan't say

5. The space was …
Private 1 2 3 4 5 6 7 Public Can't say

6. The space was …
Impressive 1 2 3 4 5 6 7 Unimpressive Can't say

7. The space was …
Inviting 1 2 3 4 5 6 7 Repelling Can't say

8. The space was …
Light 1 2 3 4 5 6 7 Dark Can't say

9. The space was …
Natural 1 2 3 4 5 6 7 Artificial Can't say

10. The space was …
Pleasant 1 2 3 4 5 6 7 Unpleasant Can't say

11. The space was …
Roomy 1 2 3 4 5 6 7 Cramped Can't say

12. The space was …
Threatening 1 2 3 4 5 6 7 Unthreatening Can't say

13. The space was …
Well scaled 1 2 3 4 5 6 7 Poorly scaled Can't say

Part D - Description of Experience

1. How did you feel about your sense of orientation in the space?

Well oriented 1 2 3 4 5 6 7 Not at all well oriented

2. How frequently did you feel disoriented or confused about where you were in the space.

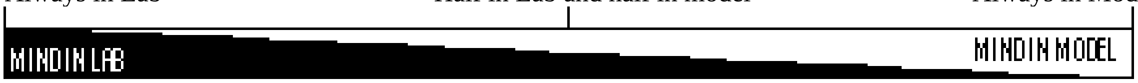
Never 1 2 3 4 5 6 7 Often

If yes, please rate your feelings…

Not the least worried 1 2 3 4 5 6 7 Very worried

3. [Question 3 - 5 are for simulation viewers only]
During the walk through of the model, where would you say your mind was?
(Scratch a mark on the line which represents the portion of time your mind was in the Laboratory versus the time your mind was in the model).

Always in Lab Half in Lab and half in model Always in Model



4. While you were exploring the spaces, would you say that you

Forgot entirely that you were in the laboratory 1 2 3 4 5 6 7 Never forgot that you were in the laboratory.

5. While you were exploring the spaces, would you say that you

Completely aware that this was a simulation 1 2 3 4 5 6 7 Forgot that this was a simulation

Part E - Evaluation of the Presentation Method [This portion is for simulation viewers only]

In the earlier parts of this questionnaire, we were interested in how you perceived the volumes. Now we would like to get your reactions to the presentation method you experienced (monitor, eyephones fixed, eyephones tracked).

I. General Reactions

A. Please list up to three things which most annoyed you about the presentation and that interfered with your ability to size up volumes of the model.

1.
2.
3.

B. Please list up to three things which would make your perception of the <u>volumes</u> of the real place differ from your perception of the volumes when viewing the model.

1.
2.
3.

II. Would the kind of method you experienced be a minimally adequate visual presentation for…

…deciding where to place furniture in the museum

Not acceptable for professional practice	-5	-4	-3	-2	-1	0	1	2	3	4	5	Completely adequate for professional practice

…deciding where to place the art work

Not acceptable for professional practice	-5	-4	-3	-2	-1	0	1	2	3	4	5	Completely adequate for professional practice

…getting a general understanding of the volumes and transitions

Not acceptable for professional practice	-5	-4	-3	-2	-1	0	1	2	3	4	5	Completely adequate for professional practice

…forming an opinion at a public hearing

Not acceptable for professional practice	-5	-4	-3	-2	-1	0	1	2	3	4	5	Completely adequate for professional practice

III. Please comment on the hardware.

Display: How did it help/inhibit you in your task of evaluating the volumes you visited?

Spaceball: How did it help/inhibit you in your task of evaluating the volumes you visited?

IV. Areas of Improvement.

As architects, we could use this technology to predict the feel of the volumes we create before they are built. But before we can do this, it is essential to measure exactly to what extent our sense of space in virtual reality models is predictive of how we will sense the real space. With this in mind, what most important improvements would you recommend to increase the fidelity of virtual spaces in predicting our perception of real volumes?

1.
2.
3.

Part F - Tell us a little about yourself

1. Profession/Occupation:

2. Age (circle one):
under 25 26-35 36-45 46-55 56-65 66-75 over 75

3. Gender (circle one):
Male Female

4. Have you ever been to the Henry Art Gallery (circle one)?
yes no {If you have not been there, circle "no" and skip to question 5.}

(Simulation viewers) Did you recognize that the model was of the Henry Art Gallery?
yes no

How many times have you visited the Henry Art Gallery (circle one)?
1 2-4 5 and over

How recent was your last visit (circle one)? Less than…
3 months ago 1 year ago 3 years ago 10 years ago over 10 years ago

How well would you say you remember the spaces in the Henry Art Gallery?

Vague memory 1 2 3 4 5 6 7 Know it like the palm of my hand

5. What is your experience with recent video games (last couple of years)?

Never played 1 2 3 4 5 6 7 Play every day

6. What is your experience with computer simulations (please list: C.A.D, Boeing Flight Simulator, etc…).

Simulation (list)	Experience (circle one)		
____________________	Fair	Good	Excellent
____________________	Fair	Good	Excellent
____________________	Fair	Good	Excellent

7. Could we contact you at a later date for follow up experiments?
yes no

This is the end of the study. Thank you very much for your participation. Please call back around october if you are interested in the results of the study, or wait until the completion of the thesis in December 92, at which point I will send them to you. Again, thank you for your interest in this study.___

APPENDIX B. DATA FIGURES

Size Estimates - Display Condition : REAL.

Actual Dimensions of Museum Spaces in Feet.			
	Width	Length	Height
Room "A"	*23.0*	*17.6*	*14.0*
Room "G"	*48.0*	*18.6*	*14.0*
Room "D"	*47.0*	*28.0*	*20.0*

.

PARTICIPANT N°	1	2	3	4	7	8	AVERAGES	
Room "A"								
Estimate W	22.00	24.00	25.00	24.00	27.00	20.00		
Actual W	23.00	23.00	23.00	23.00	23.00	23.00		
Ratio %	0.96	1.04	1.09	1.04	1.17	0.87	1.03	Width
Estimate L	18.00	18.00	20.00	18.00	20.00	15.00		
Actual L	17.60	17.60	17.60	17.60	17.60	17.60		
Ratio %	1.02	1.02	1.14	1.02	1.14	0.85	1.03	Length
Estimate H	14.00	16.00	16.00	18.00	15.00	13.00		
Actual H	14.00	14.00	14.00	14.00	14.00	14.00		
Ratio %	1.00	1.14	1.14	1.29	1.07	0.93	1.10	Height
Room "G"								
Estimate W	60.00	42.00	45.00	42.00	45.00	35.00		
Actual W	48.00	48.00	48.00	48.00	48.00	48.00		
Ratio %	1.25	0.88	0.94	0.88	0.94	0.73	0.93	Width
Estimate L	25.00	14.00	15.00	14.00	18.00	15.00		
Actual L	18.60	18.60	18.60	18.60	18.60	18.60		
Ratio %	1.34	0.75	0.81	0.75	0.97	0.81	0.91	Length
Estimate H	16.00	17.00	16.00	12.00	17.00	13.00		
Actual H	14.00	14.00	14.00	14.00	14.00	14.00		
Ratio %	1.14	1.21	1.14	0.86	1.21	0.93	1.08	Height
Room "D"								
Estimate W	60.00	48.00	45.00	40.00	50.00	40.00		
Actual W	47.00	47.00	47.00	47.00	47.00	47.00		
Ratio %	1.28	1.02	0.96	0.85	1.06	0.85	1.00	Width
Estimate L	30.00	26.00	30.00	20.00	35.00	25.00		
Actual L	28.00	28.00	28.00	28.00	28.00	28.00		
Ratio %	1.07	0.93	1.07	0.71	1.25	0.89	0.99	Length
Estimate H	24.00	24.00	25.00	18.00	20.00	20.00		
Actual H	20.00	20.00	20.00	20.00	20.00	20.00		
Ratio %	1.20	1.20	1.25	0.90	1.00	1.00	1.09	Height
Participant Mean W	1.16	0.98	0.99	0.92	1.06	0.82	0.99	Ave. Width
Participant Mean L	1.15	0.90	1.00	0.83	1.12	0.85	0.98	Ave. Length
Participant Mean H	1.11	1.19	1.18	1.01	1.10	0.95	1.09	Ave. Height
Overall Means	1.14	1.02	1.06	0.92	1.09	0.87	1.02	Overall Average

Size Estimates - Display Condition : MONITOR.

PARTICIPANT N°	9	14	15	20	21	25	AVERAGES
Room "A"							
Estimate W	21.00	20.00	27.00	22.00	20.00	24.00	
Actual W	23.00	23.00	23.00	23.00	23.00	23.00	
Ratio %	0.91	0.87	1.17	0.96	0.87	1.04	0.97 Width
Estimate L	16.00	15.00	22.00	14.00	16.00	12.00	
Actual L	17.60	17.60	17.60	17.60	17.60	17.60	
Ratio %	0.91	0.85	1.25	0.80	0.91	0.68	0.90 Length
Estimate H	14.00	12.00	16.00	12.00	14.00	15.00	
Actual H	14.00	14.00	14.00	14.00	14.00	14.00	
Ratio %	1.00	0.86	1.14	0.86	1.00	1.07	0.99 Height
Room "G"							
Estimate W	32.00	35.00	45.00	35.00	30.00	40.00	
Actual W	48.00	48.00	48.00	48.00	48.00	48.00	
Ratio %	0.67	0.73	0.94	0.73	0.63	0.83	0.75 Width
Estimate L	18.00	16.00	20.00	17.00	15.00	15.00	
Actual L	18.60	18.60	18.60	18.60	18.60	18.60	
Ratio %	0.97	0.86	1.08	0.91	0.81	0.81	0.91 Length
Estimate H	14.00	16.00	18.00	13.00	15.00	15.00	
Actual H	14.00	14.00	14.00	14.00	14.00	14.00	
Ratio %	1.00	1.14	1.29	0.93	1.07	1.07	1.08 Height
Room "D"							
Estimate W	36.00	35.00	60.00	38.00	25.00	40.00	
Actual W	47.00	47.00	47.00	47.00	47.00	47.00	
Ratio %	0.77	0.74	1.28	0.81	0.53	0.85	0.83 Width
Estimate L	20.00	25.00	40.00	30.00	20.00	24.00	
Actual L	28.00	28.00	28.00	28.00	28.00	28.00	
Ratio %	0.71	0.89	1.43	1.07	0.71	0.86	0.95 Length
Estimate H	18.00	18.00	30.00	20.00	15.00	21.00	
Actual H	20.00	20.00	20.00	20.00	20.00	20.00	
Ratio %	0.90	0.90	1.50	1.00	0.75	1.05	1.02 Height
Participant Mean W	0.78	0.78	1.13	0.83	0.68	0.91	0.85 Ave. Width
Participant Mean L	0.86	0.87	1.25	0.93	0.81	0.78	0.92 Ave. Length
Participant Mean H	0.97	0.97	1.31	0.93	0.94	1.06	1.03 Ave. Height
Overall Means	0.87	0.87	1.23	0.90	0.81	0.92	0.93 Overall Average

Size Estimates - Display Condition : FIXED.

PARTICIPANT N°	10	12	16	19	23	24	Ave. score
Room "A"							
Estimate W	20.00	21.00	25.00	30.00	25.00	18.00	
Actual W	23.00	23.00	23.00	23.00	23.00	23.00	
Ratio %	0.87	0.91	1.09	1.30	1.09	0.78	1.01 Width
Estimate L	12.00	18.00	20.00	18.00	15.00	14.00	
Actual L	17.60	17.60	17.60	17.60	17.60	17.60	
Ratio %	0.68	1.02	1.14	1.02	0.85	0.80	0.92 Length
Estimate H	10.00	10.00	14.00	16.00	12.00	14.00	
Actual H	14.00	14.00	14.00	14.00	14.00	14.00	
Ratio %	0.71	0.71	1.00	1.14	0.86	1.00	0.90 Height
Room "G"							
Estimate W	40.00	36.00	45.00	36.00	50.00	30.00	
Actual W	48.00	48.00	48.00	48.00	48.00	48.00	
Ratio %	0.83	0.75	0.94	0.75	1.04	0.63	0.82 Width
Estimate L	18.00	18.00	20.00	16.00	15.00	14.00	
Actual L	18.60	18.60	18.60	18.60	18.60	18.60	
Ratio %	0.97	0.97	1.08	0.86	0.81	0.75	0.91 Length
Estimate H	15.00	13.00	14.00	14.00	15.00	14.00	
Actual H	14.00	14.00	14.00	14.00	14.00	14.00	
Ratio %	1.07	0.93	1.00	1.00	1.07	1.00	1.01 Height
Room "D"							
Estimate W	40.00	28.00	50.00	30.00	40.00	30.00	
Actual W	47.00	47.00	47.00	47.00	47.00	47.00	
Ratio %	0.85	0.60	1.06	0.64	0.85	0.64	0.77 Width
Estimate L	25.00	18.00	35.00	18.00	24.00	18.00	
Actual L	28.00	28.00	28.00	28.00	28.00	28.00	
Ratio %	0.89	0.64	1.25	0.64	0.86	0.64	0.82 Length
Estimate H	18.00	16.00	22.00	20.00	20.00	18.00	
Actual H	20.00	20.00	20.00	20.00	20.00	20.00	
Ratio %	0.90	0.80	1.10	1.00	1.00	0.90	0.95 Height
Participant Mean W	0.85	0.75	1.03	0.90	0.99	0.68	0.87 Ave. Width
Participant Mean L	0.85	0.88	1.15	0.84	0.84	0.73	0.88 Ave. Length
Participant Mean H	0.90	0.81	1.03	1.05	0.98	0.97	0.96 Ave. Height
Overall Means	0.86	0.81	1.07	0.93	0.94	0.79	0.90 Overall Average

Size Estimates - Display Condition : TRACKED.

PARTICIPANT N°	11	13	17	18	22	26	Ave. score	
Room "A"								
Estimate W	24.00	20.00	16.00	16.00	18.00	25.00		
Actual W	23.00	23.00	23.00	23.00	23.00	23.00		
Ratio %	1.04	0.87	0.70	0.70	0.78	1.09	0.86	Width
Estimate L	16.00	14.00	11.00	12.00	14.00	18.00		
Actual L	17.60	17.60	17.60	17.60	17.60	17.60		
Ratio %	0.91	0.80	0.63	0.68	0.80	1.02	0.80	Length
Estimate H	11.00	11.00	12.00	11.00	12.00	15.00		
Actual H	14.00	14.00	14.00	14.00	14.00	14.00		
Ratio %	0.79	0.79	0.86	0.79	0.86	1.07	0.86	Height
Room "G"								
Estimate W	32.00	29.00	30.00	30.00	30.00	48.00		
Actual W	48.00	48.00	48.00	48.00	48.00	48.00		
Ratio %	0.67	0.60	0.63	0.63	0.63	1.00	0.69	Width
Estimate L	14.00	14.00	16.00	12.00	15.00	18.00		
Actual L	18.60	18.60	18.60	18.60	18.60	18.60		
Ratio %	0.75	0.75	0.86	0.65	0.81	0.97	0.80	Length
Estimate H	12.00	12.00	14.00	12.00	13.00	12.00		
Actual H	14.00	14.00	14.00	14.00	14.00	14.00		
Ratio %	0.86	0.86	1.00	0.86	0.93	0.86	0.89	Height
Room "D"								
Estimate W	34.00	30.00	30.00	30.00	35.00	40.00		
Actual W	47.00	47.00	47.00	47.00	47.00	47.00		
Ratio %	0.72	0.64	0.64	0.64	0.74	0.85	0.71	Width
Estimate L	20.00	23.00	24.00	18.00	24.00	25.00		
Actual L	28.00	28.00	28.00	28.00	28.00	28.00		
Ratio %	0.71	0.82	0.86	0.64	0.86	0.89	0.80	Length
Estimate H	15.00	14.00	24.00	16.00	20.00	20.00		
Actual H	20.00	20.00	20.00	20.00	20.00	20.00		
Ratio %	0.75	0.70	1.20	0.80	1.00	1.00	0.91	Height
Participant Mean W	0.81	0.70	0.65	0.65	0.72	0.98	0.75	Ave. Width
Participant Mean L	0.79	0.79	0.78	0.66	0.82	0.96	0.80	Ave. Length
Participant Mean H	0.80	0.78	1.02	0.81	0.93	0.98	0.89	Ave. Height
Overall Means	0.80	0.76	0.82	0.71	0.82	0.97		Overall Average

Angle Estimate - Display condition : REAL

Actual Angle to Target.		
	Angle from closest normal	
Target 1	*-21.4*	*(To right of normal)*
Target 2	*-40.0*	*(To right of normal)*
Target 3	*17.2*	*(To left of normal)*

PARTICIPANT N°	1	2	3	4	7	8	Ave. score
Target 1							
Estimate to the Normal	-34.9	-34.9	-31.2	-36.5	-32.9	-29.6	
Actual Angle to Target	-21.4	-21.4	-21.4	-21.4	-21.4	-21.4	
Error from Target	13.5	13.5	9.8	15.1	11.5	8.2	11.9
Ease	9	8	4	5	2	8	6.0
Confidence	9	6	6	8	8	2	6.5
Target 2							
Estimate to the Normal	-51.6	-52.6	-40.0	-50.0	-52.9	-53.7	
Actual Angle to Target	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	
Error from Target	11.6	12.6	0.0	10.0	12.9	13.7	10.1
Ease	3	4	2	5	2	7	3.8
Confidence	9	7	9	8	8	2	7.2
Target 3							
Estimate to the Normal	22.4	22.7	23.3	16.6	28.0	23.8	
Actual Angle to Target	17.2	17.2	17.2	17.2	17.2	17.2	
Error from Target	-5.20	-5.50	-6.10	0.60	-10.80	-6.60	
Normalized Error from Target	5.20	5.50	6.10	-0.60	10.80	6.60	5.6
Ease	9	8	6	7	4	8	7.0
Confidence	7	3	4	6	5	2	4.5
Particip. Ease Mean	7.0	6.7	4.0	5.7	2.7	7.7	5.6
Particip. Conf. Mean	8.3	5.3	6.3	7.3	7.0	2.0	6.1

Angle Estimate - Display condition : MONITOR.

PARTICIPANT N°	9	14	15	20	21	25	Ave. score
Target 1							
Estimate to the Normal	2.7	1.0	-5.7	-12.5	-6.2	-27.9	
Correction for Mono.	13.0	13.0	13.0	13.0	13.0	13.0	
Error from Target	15.7	14.0	7.3	0.5	6.8	-14.9	4.9
Ease	6	1	3	4	7	2	
Confidence	7	8	8	8	5	7	7.2
Target 2							
Estimate to the Normal	-14.1	-1.2	2.2	-11.5	-4.0	3.8	
Correction for Mono.	13.0	13.0	13.0	13.0	13.0	13.0	
Error from Target	-1.1	11.8	15.2	1.5	9.0	16.8	8.9
Ease	8	1	2	8	4	2	4.2
Confidence	1	9	9	3	4	8	5.7
Target 3							
Estimate to the Normal	-17.0	-7.6	-6.8	-18.0	-10.3	-18.2	
Correction for Mono.	13.0	13.0	13.0	13.0	13.0	13.0	
Error from Target	-4.0	5.4	6.2	-5.0	2.7	-5.2	0.0
Normalized Error from Target	4.0	-5.4	-6.2	5.0	-2.7	5.2	0.0
Ease	5	2	3	9	3	5	4.5
Confidence	4	8	8	2	7	6	5.8
Particip. Ease Mean	6.3	1.3	2.7	7.0	4.7	3.0	4.2
Particip. Conf. Mean	4.0	8.3	8.3	4.3	5.3	7.0	6.2

The Correction Value of 13° corrects
for the SpaceBall Values which record
the direction the observer is facing for stereoscopic viewing conditions. It has to be
corrected for the monoscopic viewing condition.

Angle Estimate - Display condition : FIXED.

PARTICIPANT N°	10	12	16	19	23	24	Ave. score
Target 1							
Error from Target	6.6	11.5	-9.7	10.8	28.1	14.4	10.3
Ease	7	5	6	7	7	2	5.7
Confidence	5	5	7	8	5	8	6.3
Target 2							
Error from Target	4.8	-7.6	6.0	16.7	11.5	13.0	7.4
Ease	2	3	3	3	2	2	2.5
Confidence	8	7	6	8	8	8	7.5
Target 3							
Error from Target	-10.9	-25.8	8.6	-5.1	-10.3	-8.8	
Normalized Error from Target	10.9	25.8	-8.6	5.1	10.3	8.8	8.7
Ease	3	7	2	2	2	2	3.0
Confidence	7	4	8	9	9	8	7.5
Particip. Ease Mean	4.0	5.0	3.7	4.0	3.7	2.0	3.7
Particip. Conf. Mean	6.7	5.3	7.0	8.3	7.3	8.0	7.1

Angle Estimate Data - Display condition : TRACKED.

PARTICIPANT N°	11	13	17	18	22	26	Ave. score
Target 1							
Error from Target	5.90	24.50	17.40	21.40	0.00	9.60	13.13
Ease	3	9	3	2	3	3	3.83
Confidence	7	2	10	8	6	10	7.17
Target 2							
Error from Target	18.80	28.90	2.20	12.60	18.00	8.90	14.90
Ease	3	8	1	5	1	3	3.50
Confidence	8	3	10	5	7	8	6.83
Target 3							
Error from Target	-11.60	-2.80	-2.40	7.80	-0.40	-15.40	
Normalized Error from Target	11.60	2.80	2.40	-7.80	0.40	15.40	4.13
Ease	3	5	8	9	1	3	4.83
Confidence	8	4	8	2	8	8	6.33
Particip. Ease Mean	3.0	7.3	4.0	5.3	1.7	3.0	4.1
Particip. Conf. Mean	7.7	3.0	9.3	5.0	7.0	8.7	6.8

Descriptive Task - Display Condition : REAL.

	Question Number												
Participant number	1	2	3	4	5	6	7	8	9	10	11	12	13
1	2	2	5	2	7	4	2	2	2	2	2	6	2
2	6	3	6	1	3	2	2	1	6	2	1	5	2
3	3	4	3	2	6	2	3	3	6	2	2	4	2
4	2	2	5	1	6	2	1	1	5	2	1	6	2
7	5	2	5	1	3	2	2	3	7	3	2	6	1
8	4	4	6	2	6	4	5	3	6	3	1	7	2
Standard Deviation	1.6	1.0	1.1	0.5	1.7	1.0	1.4	1.0	1.8	0.5	0.5	1.0	0.4
Average	3.7	2.8	5.0	1.5	5.2	2.7	2.5	2.2	5.3	2.3	1.5	5.7	1.8

Descriptive Task Data Results- Display Condition : MONITOR.

	Question Number												
Participant number	1	2	3	4	5	6	7	8	9	10	11	12	13
9	4	3	5	2	6	6	5	2	7	6	2	7	6
14	3	2	6	3	7	2	2	1	5	2	3	7	2
15	2	2	4	1	5	2	2	1	2	2	1	7	2
20	2	3	3	1	6	3	3	2	5	2	2	7	2
21	4	5	6	2	6	3	3	2	6	3	3	6	2
25	3	5	3	1	7	2	3	2	7	2	2	5	2
Standard Deviation	0.9	1.4	1.4	0.8	0.8	1.5	1.1	0.5	1.9	1.6	0.8	0.8	1.6
Average	3.0	3.3	4.5	1.7	6.2	3.0	3.0	1.7	5.3	2.8	2.2	6.5	2.7

Descriptive Task Data Results- Display Condition : FIXED.

	Question Number												
Participant number	1	2	3	4	5	6	7	8	9	10	11	12	13
10	3	3	6	2	7	2	2	2	3	2	2	6	1
12	3	3	6	2	6	4	2	2	6	5	6	6	3
16	3	1	7	3	4	4	1	2	3	1	1	7	1
19	2	2	7	2	7	2	2	2	2	2	2	7	2
23	3	2	6	2	7	2	2	2	3	2	1	7	2
24	5	1	7	3	7	5	1	1	7	2	1	4	1
Standard Deviation	1.0	0.9	0.5	0.5	1.2	1.3	0.5	0.4	2.0	1.4	1.9	1.2	0.8
Average	3.2	2.0	6.5	2.3	6.3	3.2	1.7	1.8	4.0	2.3	2.2	6.2	1.7

Descriptive Task - Display Condition : TRACKED.

	Question Number												
Participant number	1	2	3	4	5	6	7	8	9	10	11	12	13
11	4	2	4	1	4	3	3	4	4	2	1	7	2
13	3	3	4	3	5	3	5	2	3	2	1	5	4
17	3	3	7	2	7	2	2	2	5	3	1	7	2
18	5	3	7	1	6	2	4	3	5	3	1	4	2
22	1	2	7	1	6	6	4	1	6	1	1	6	1
26	3	2	7	1	7	2	2	1	5	2	1	7	2
Standard Deviation	1.3	0.5	1.5	0.8	1.2	1.5	1.2	1.2	1.0	0.8	0.0	1.3	1.0
Average	3.2	2.5	6.0	1.5	5.8	3.0	3.3	2.2	4.7	2.2	1.0	6.0	2.2

Sketches - Display Conditions : All

MONITOR

	Sketch Accuracy	Memory of Visit	Relative Sizes of Spaces	Easiest Space to Size-Estimate	Most Pleasant	Least Pleasant
Participant						
9	3	3	1	A	1	7
14	3	3	3	n/a	4	7
15	3	3	3	C	4	2
20	0	0	1	C	4	2
21	3	3	3	D	4	1
25	2	2	3	D	4	6
AVERAGE	2.3	2.3	2.3			
FIXED						
Participant						
10	3	3	3	D	4	5
12	0	0	0	C	1	4
16	3	3	3	D	4	2
19	2	3	0	n/a	4	2
23	3	3	2	D	4	6
24	3	3	2	C	4	6
AVERAGE	2.3	2.5	1.7			
TRACKED						
Participant						
11	3	3	3	G	4	7
13	3	2	2	C	7	2
17	3	3	2	A	4	7
18	2	3	3	A	4	6
22	3	3	2	D	4	n/a
26	3	3	3	A	4	3
AVERAGE	2.8	2.8	2.5			
REAL						
Participant						
1	3	3	3	C	1	7
2	3	3	2	A	4	5
3	3	3	3	C	4	7
4	3	3	3	E	4	5
7	3	3	2	D	4	7
8	3	3	2	A	2	1
AVERAGE	3.0	3.0	2.5			

General Experience Evaluation - Display Conditions : ALL

Self-reported expressions for sense of Orientation and "Presence". Scales are from 1 to 10 (refer to questionnaire in Appendix A.)

REAL

Participant number	Sense of Orientation	Freqency got lost	Level of unease	Mind's focus	Forgot Laboratory	Forgot Simulation
1	2	1	1	n/a	n/a	n/a
2	1	1	1	n/a	n/a	n/a
3	1	1	n/a	n/a	n/a	n/a
4	2	2	1	n/a	n/a	n/a
7	2	1	n/a	n/a	n/a	n/a
8	1	1	n/a	n/a	n/a	n/a
Average	1.5	1.2	1.0	n/a	n/a	n/a

MONITOR

Participant number	Sense of Orientation	Freqency got lost	Level of unease	Mind's focus	Forgot Laboratory	Forgot Simulation
9	4	4	1	10	1	1
14	1	1	n/a	9	2	4
15	2	2	n/a	1	7	1
20	3	3	3	8	2	5
21	2	4	3	8	5	2
25	1	1	n/a	2	7	1
Average	2.2	2.5	2.3	6.3	4.0	2.3

FIXED

Participant number	Sense of Orientation	Freqency got lost	Level of unease	Mind's focus	Forgot Laboratory	Forgot Simulation
10	2	5	3	7	4	2
12	6	6	1	8	2	2
16	1	2	1	7	3	2
19	1	3	1	6	6	1
23	3	4	2	9	2	1
24	1	2	1	7	2	4
Average	2.3	3.7	1.5	7.3	3.2	2.0

TRACKED

Participant number	Sense of Orientation	Freqency got lost	Level of unease	Mind's focus	Forgot Laboratory	Forgot Simulation
11	2	1	1	10	2	1
13	5	6	4	9	3	5
17	2	2	1	9	2	1
18	3	3	4	9	2	3
22	1	1	n/a	9	7	1
26	1	2	n/a	7	7	1
Average	2.3	2.5	2.5	8.8	3.8	2.0

Participant Evaluation of Interface. - Display Conditions : ALL

Participants described three aspects about the interface which made the Size Task difficult.

	DISPLAY CONDITION			
	Monitor	Fixed	Tracked	*All Simulations*
SpaceBall				
Combined Translation & Rotation	2	0	0	2
Difficult to use	5	2	1	8
SubTotal	7	2	1	10
EyePhones - Display				
Narrow field of view	3	1	2	6
Low Resolution	2	1	4	7
Frame dropouts	1	0	0	1
Optical Distortion	0	2	1	3
Bad Depth perception cues	0	1	0	1
SubTotal	6	5	7	18
EyePhones - Ergonomics				
Don't hold in place	0	0	1	1
Foggy-Perspiration	0	0	1	1
Heavy	0	1	0	1
SubTotal	0	1	2	3
Interface - Other				
Tactile feedback of surfaces	0	0	1	1
Head tracking needed	0	2	0	2
Dizziness	0	0	1	1
SubTotal	0	2	2	4
Interaction				
Non-variable speed of movement	0	0	2	2
Turning view point speed	1	0	0	1
Lag	0	0	1	1
Physical act of WALKING	0	1	1	2
Jerky movement/slow update rate	1	0	1	2
SubTotal	2	1	5	8

Participant Evaluation of Interface. - Continued

	DISPLAY CONDITION			
	Monitor	Fixed	Tracked	*All Simulations*
Model				
Need natural light	2	2	1	5
Need shadows	1	1	2	4
Scale elements/detail -not enough	4	5	4	13
Need better color	1	2	1	4
"Jaggies"	1	0	0	1
Need texture	1	3	1	5
SubTotal	10	13	9	32
Model - Extensions				
Sound	0	2	2	4
Animated People	1	0	0	1
Air, breeze	0	0	1	1
Users' body - cues	0	0	2	2
Smells	0	1	0	1
SubTotal	1	3	5	9
How the Visit was conducted				
Lack of training - spaceball	0	0	1	1
Tracked visit	0	1	0	1
Getting positioned in corners	0	1	0	1
Move around more before task	0	1	1	2
Distractions from laboratory	1	0	0	1
SubTotal	1	3	2	6

Participant Profile - Display Condition : ALL

DISPLAY CONDITION	Ave. Age	Gender (M=0)	Been to Museum (No=0)	Number of visits	Last visit (years)	Memory of Museum (1 to 10)	Video Game Experience (1 to 10)	Simulation Experience
MONITOR								
	30	0	0	n/a	n/a	n/a	1	Fair
	30	0	1	Over 5	3	5	1	Good
	30	0	1	1	10	1	2	Excellent
	30	0	1	Over 5	0.25	7	1	None
	30	0	0	n/a	n/a	n/a	4	Excellent
	30	0	1	Over 5	0.25	4	2	Good
Average	30	0	0.7	Over 5	3 years	4.3	1.8	Good
FIXED								
	40	0	1	Over 5	0.25	6	1	Fair
	40	0	1	1	1	3	3	Excellent
	30	0	1	<2-4>	1	2	3	Good
	30	1	1	Over 5	1	4	1	None
	30	0	0	n/a	n/a	n/a	2	Excellent
	30	0	1	1	1	2	1	None
Average	33	0.2	0.8	<2-4>	1 year	3.4	1.8	Good
TRACKED								
	30	1	1	<2-4>	0.25	5	1	None
	60	0	1	Over 5	1	7	2	None
	30	1	1	<2-4>	1	4	1	Fair
	20	1	0	n/a	n/a	n/a	2	None
	30	0	0	n/a	n/a	n/a	2	Excellent
	30	0	1	1	1	2	1	None
Average	33	0.5	0.7	<2-4>	1	4.5	1.5	Fair
REAL								
	30	1	1	Over 5	1	6	1	None
	30	0	1	Over 5	0.25	6	1	Good
	30	0	1	Over 5	1	6	2	Excellent
	20	0	1	Over 5	0.25	6	4	Fair
	30	0	1	<2-4>	0.25	6	2	Good
	30	0	1	<2-4>	0.25	6	1	Fair
Average	28	0.2	1	Over 5	0.5	6	1.8	Fair-Good

APPENDIX C. STATISTICS TABLES

Unless otherwise noted, all statistics are one-factor ANOVAs calculated at the 95% interval. They include a table for the sums of squares, a table for the means and a table for individual differences if applicable.

Table C.1 - Horizontal estimates as a function of display.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	.76	.25	8.95
Within groups	140	3.94	.03	p = .0001
Total	143	4.7		

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	36	.88	.19	.03
Fixed	36	.87	.18	.03
Tracked	36	.78	.13	.02
Real	36	.98	.16	.03

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	.01	.08	.02	.25
Monitor vs. Tracked	.11	.08*	2.45	2.71
Monitor vs. Real	-.1	.08*	2.03	2.47
Fixed vs. Tracked	.1	.08*	2.03	2.47
Fixed vs. Real	-.11	.08*	2.45	2.71
Tracked vs. Real	-.2	.08*	8.93*	5.18

* Significant at 95%

Table C.2 - Vertical estimates as a function of display.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	.42	.14	7.17
Within groups	68	1.32	.02	p = .0003
Total	71	1.73		

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	18	1.03	.17	.04
Fixed	18	.96	.12	.03
Tracked	18	.89	.12	.03
Real	18	1.09	.13	.03

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	.07	.09	.86	1.61
Monitor vs. Tracked	.14	.09*	3.11*	3.05
Monitor vs. Real	-.06	.09	.56	1.29
Fixed vs. Tracked	.07	.09	.7	1.45
Fixed vs. Real	-.13	.09*	2.8*	2.9
Tracked vs. Real	-.2	.09*	6.3*	4.35

* Significant at 95%

Table C.3 - Ease of making size estimates as a function of display.

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	32.28	10.76	5
Within groups	68	146.33	2.15	p = .0034
Total	71	178.61		

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	18	4.56	1.25	.29
Fixed	18	3.72	1.13	.27
Tracked	18	4.67	1.61	.38
Real	18	5.61	1.79	.42

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	.83	.98	.97	1.7
Monitor vs. Tracked	-.11	.98	.02	.23
Monitor vs. Real	-1.06	.98*	1.55	2.16
Fixed vs. Tracked	-.94	.98	1.24	1.93
Fixed vs. Real	-1.89	.98*	4.97*	3.86
Tracked vs. Real	-.94	.98	1.24	1.93

* Significant at 95%

Table C.4 - Confidence in size estimates as a function of display.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	25.22	8.41	3.59
Within groups	68	159.22	2.34	p = .018
Total	71	184.44		

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	18	5.72	1.6	.38
Fixed	18	7.22	.81	.19
Tracked	18	6.33	1.78	.42
Real	18	5.83	1.72	.41

Table C.5 - Horizontal estimates as a function gender.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	1	.28	.28	9.07
Within groups	142	4.42	.03	p = .0031
Total	143	4.7		

Model II estimate of between component variance = .01

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Men	114	.9	.19	.02
Women	30	.79	.14	.03

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Men vs. Women	.11	.07*	9.07*	3.01

* Significant at 95%

Table C.6 - Target as a function of normalized angle.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	2	499.98	249.99	3.54
Within groups	69	4874.52	70.65	p = .0344
Total	71	5374.5		

Model II estimate of between component variance = 7.47

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
1	24	10.06	9.54	1.95
2	24	10.32	7.74	1.58
3	24	4.61	7.81	1.59

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
1 vs. 2	-.26	4.84	.01	.11
1 vs. 3	5.45	4.84*	2.53	2.25
2 vs. 3	5.72	4.84*	2.78	2.36

* Significant at 95%

Table C.7 - Target and display as a function of the normalized angle estimate (Two-factor ANOVA).

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Display (A)	3	373.99	124.66	1.78	.1612
Pt. (B)	2	499.98	249.99	3.56	.0345
AB	6	290.56	48.43	.69	.6583
Error	60	4209.97	70.17		

Table C.8 - Normalized angle estimates as a function of display.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	373.99	124.66	1.7
Within groups	68	5000.51	73.54	p = .1762
Total	71	5374.5		

Model II estimate of between component variance = 2.84

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	18	4.58	8.63	2.03
Fixed	18	8.8	10.16	2.39
Tracked	18	10.72	9.76	2.3
Real	18	9.22	4.6	1.08

Table C.9 - Normalized angle variance from the mean as a function of display (One-factor ANOVA at the 90% interval)

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	204.78	68.26	2.46
Within groups	68	1890.31	27.8	p = .0705
Total	71	2095.09		

Model II estimate of between component variance = 2.25

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	18	6.77	5.09	1.2
Fixed	18	7.22	6.93	1.63
Tracked	18	8.01	5.23	1.23
Real	18	3.58	3.16	.74

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	-.45	3.12	.02	.25
Monitor vs. Tracked	-1.24	3.12	.17	.7
Monitor vs. Real	3.2	3.12*	1.1	1.82
Fixed vs. Tracked	-.79	3.12	.07	.45
Fixed vs. Real	3.64	3.12*	1.43	2.07
Tracked vs. Real	4.43	3.12*	2.12	2.52

* Significant at 92%

Table C.10 - Ease of angle task as a function of display.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	37.778	12.593	2.082
Within groups	68	411.333	6.049	p = .1107
Total	71	449.111		

Model II estimate of between component variance = .364

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	18	4.167	2.526	.595
Fixed	18	3.722	2.109	.497
Tracked	18	4.056	2.689	.634
Real	18	5.611	2.477	.584

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	.444	1.636	.098	.542
Monitor vs. Tracked	.111	1.636	.006	.136
Monitor vs. Real	-1.444	1.636	1.035	1.762
Fixed vs. Tracked	-.333	1.636	.055	.407
Fixed vs. Real	-1.889	1.636*	1.769	2.304

* Significant at 95%

Table C.11 - Confidence in the angle estimates as a function of display.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	12.93	4.31	.81
Within groups	68	360.94	5.31	p = .4916
Total	71	373.88		

Model II estimate of between component variance = -.06

Table C.12 - Description of space as a function of display for question 2.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	13	4.33	3.88
Within groups	20	22.33	1.12	p = .0245
Total	23	35.33		

Model II estimate of between component variance = .54

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	6	4	1.55	.63
Fixed	6	2	.89	.37
Tracked	6	2.5	.55	.22
Real	6	2.83	.98	.4

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	2	1.27*	3.58*	3.28
Monitor vs. Tracked	1.5	1.27*	2.01	2.46
Monitor vs. Real	1.17	1.27	1.22	1.91
Fixed vs. Tracked	-.5	1.27	.22	.82
Fixed vs. Real	-.83	1.27	.62	1.37
Tracked vs. Real	-.33	1.27	.1	.55

* Significant at 95%

Table C.13 - Description of space as a function of display for question 3.

Analysis of Variance Table

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between groups	3	22.12	7.38	5.36
Within groups	20	27.5	1.38	p = .0071
Total	23	49.62		

Model II estimate of between component variance = 1

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Monitor	6	4	1.26	.52
Fixed	6	6.5	.55	.22
Tracked	6	6	1.55	.63
Real	6	5	1.1	.45

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Monitor vs. Fixed	-2.5	1.41*	4.55*	3.69
Monitor vs. Tracked	-2	1.41*	2.91	2.95
Monitor vs. Real	-1	1.41	.73	1.48
Fixed vs. Tracked	.5	1.41	.18	.74
Fixed vs. Real	1.5	1.41*	1.64	2.22
Tracked vs. Real	1	1.41	.73	1.48

* Significant at 95%

APPENDIX D. INTERFACE HARDWARE.

Fig. D.1 - The Spaceball.

The Spaceball. A Device for Controlling the Viewpoint.

The Spaceball is a pressure sensitive device, in the form of a large softball (Fig. D.1). The Spaceball is sensitive to both torque and direct force. It has 6 degrees of freedom, allowing movement in the X, Y and Z axis as well as the three rotations, Pitch, Yaw and Roll. It is generally used to control the translation and rotation of objects in interactive 3D environments. In this study, it is used in an unconventional way because the object it controls is the viewpoint.

In the interest of minimizing confusion while using the tool, and to best simulate the normal movement of the eyes while walking, the degrees of freedom of the Spaceball had to be constrained. Movement was constrained to the forward direction. Participants were prevented from backing up because preliminary studies showed that people tend to back-up much more often in virtual environments than in real life. This factor was a source of confounding error. By prohibiting the backward movement, participants had to turn around when they wished to leave a space. This was closer to real life behavior. It should be noted that this constraint on movement came at the cost of increased difficulty in navigation. People often find themselves close to flat surface which fill their entire field of view with one indistinguishable polygon color. At these moments, it is very difficult to know the evolution of one's position. Being able to back up is essential for not getting lost while navigating in virtual environments.

In the non-tracked conditions, the rotation of the viewpoint was constrained to pitch and yaw. In the Tracked condition, the rotation of the viewpoint was controlled by the Polhemus tracker.

The rate of movement was fixed to an approximate walking speed (1.5 meters/second). Although the Spaceball is sensitive to varying pressure, preliminary studies showed that when given a chance, people tend to go as fast as they can all the time. By controlling the speed, individual differences in rate of movement would not be a confounding factor.

The Spaceball was selected as a movement device because it was the only one which could be used in all three simulation conditions. While there are better adapted position tracked devices available, such as the dataglove and the wand, none of these devices would have made any sense in the Monitor condition which requires a space stabilized device.

The Spaceball was clumsy in the Monitor and Fixed conditions because it controlled both the translation and rotation of the view point. It was clumsy in the Tracked condition because it was fixed to the table. This is particularly apparent when the participants are coming back south to the entrance of the museum, and it lead to rather uncomfortable postures.

Particularly true to the Tracked condition, using the Spaceball also had the effect of "grounding" participants to the laboratory. Traditional virtual interface movement devices are not firmly attached to the real space, and the only physical contact participants have with the laboratory is through their feet. As a result, they often lose all sense of their orientation to the lab, and when they remove the eyephones, many express surprise as to the direction they are facing. Having the table and the fixed Spaceball mounted on it greatly increased peoples’ sense direction.

Fig. D.2 - The VPL Eyephones (customized).

The Eyephone and Head Position Tracking Device.

The Eyephones (Head Mounted Displays) are stereoscopic color video displays placed inside goggles. Black rubber sidings completely block out any incoming light outside of the video display (Fig. D.2).

The Head Tracking device is the Polhemus. The receptor is the little cube located at the top of the eyephones. The position of the receptor relative to the actual location of the eyes is corrected for in the programming.

APPENDIX E. OPTICAL DISTORTIONS.

A mini study was conducted in an attempt to measure the degree of optical distortion present in the VPL Eyephones. This consists of measuring the subtended angle of an object in real space relative to a person's eye, and comparing that value to the same object when viewed through the optics of the eyephones. Very accurate measurement of this subtended angle would require expensive equipment. A simpler method consists of comparing photographs of each medium. It was judged that this method of comparison would be sufficiently precise at this stage.

A computer model of the laboratory space was built and placed into the virtual interface system. The model was built using the exact same scale as the museum. Photographs of the same view were taken from the exact same location in real and virtual laboratory. 50mm lens were used for the photographs (Fig. E.1, E.2, E.3 on the following page).

The 50mm lens have a narrower field of view than what is displayed in the eyephones, so only the center most portion can be compared across all conditions. Also, the photograph through the eyephones is a little out of focus because the lens could not be placed as close to the optics as the eyes.

Distortion Results.

The Eyephone condition appears to be quite similar to the Real condition. This can be verified by comparing the angle at which the walls meet the corner. There is however a slight distortion apparent in the bending of the "frames". The photograph could not show how this distortion increases towards the edges of the field of view because it was outside the range of the 50 mm lenses.

The Monitor condition is the same video image as the Eyephone condition only without the magnifying optics. It too appears to be very similar to the photograph of the real space.

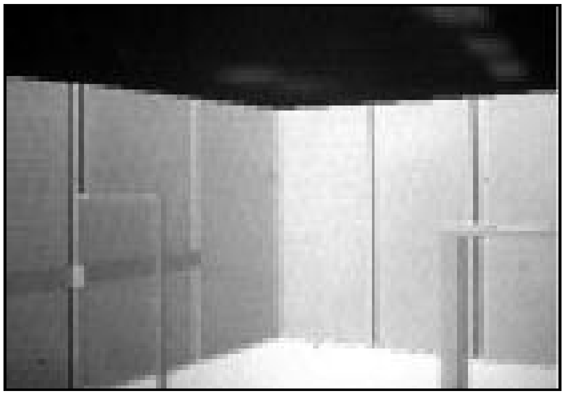


Fig. E.1 - Photograph of the image on the monitor.

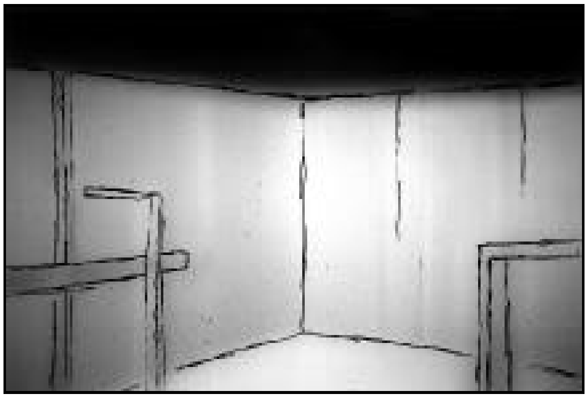


Fig. E.2 - Photograph through the VPL eyephones.

Fig. E.3 - Photograph of the real laboratory.

In conclusion, these photographs indicate that there is a small optical distortion, but that this distortion could not be the only factor for explaining the degree to which distances are underestimated in virtual environments.