

Spatial Perception in Perspective Displays as a Function of Field-of-view
and Virtual Environment Enhancements Based on Visual Momentum

Techniques

by

Dennis Clay Neale

Thesis

submitted to the Faculty of the

Virginia Polytechnic Institute and State University

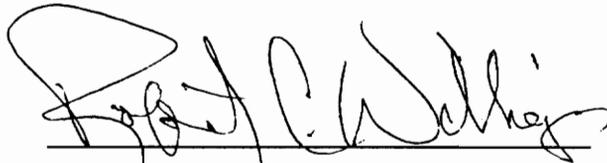
in partial fulfillment of the requirements for the degree of

Master of Science

in

Industrial and Systems Engineering

APPROVED:



Dr. Robert C. Williges, Chair



Dr. Albert M. Prestrude



Dr. Walter W. Wierwille

May, 1995

Blacksburg, Virginia

Key words: Perspective display, Geometric field of view, Field of view,
Virtual environments, Visual momentum, Spatial perception

C.2

LD
5685
Y855
1975
N435
C.2

Spatial Perception in Perspective Displays as a Function of Field-of-view
and Virtual Environment Enhancements Based on Visual Momentum
Techniques

by

Dennis Clay Neale

Committee Chair: Robert C. Williges
Industrial and Systems Engineering

ABSTRACT

This study investigated perceptual and cognitive issues relating to manipulations in geometric field-of-view (GFOV) in perspective displays and the effects of incorporating virtual environment enhancements in the interface based on visual momentum (VM) techniques. Geometric field-of-view determines the field-of-view (FOV) for perspective displays. Systematic errors in size and distance have been shown to occur in perspective displays as the result of changes in the GFOV. Furthermore, as humans' normal FOV becomes restricted, their ability to acquire spatial information is reduced resulting in an incomplete formulation and representation of the visual world. The magnitude of the resulting biases increase as task difficulty increases. It was predicted that as VM increases in

the interface, the ability to overcome problems associated with restricted FOVs will also increase.

Sixty participants who were pre-tested for spatial ability were required to navigate through a virtual office building while estimating space dimensions and performing spatial orientation and representation tasks. A 3 x 2 x 2 mixed-subjects design compared three levels of GFOV, two levels of VM, and two levels of Difficulty.

The results support the hypothesis that 60° is the optimum GFOV for perspective displays. VM increased accuracy for space dimension estimates, reduced direction judgment errors, improved distance estimates when task difficulty was increased, improved participants' cognitive maps, and reduced the error for reconstructing the spatial layout of objects in a virtual space. The results also support the hypothesis that wider FOVs are needed to accurately perform spatial orientation and representation tasks in virtual environments. Spatial ability was also shown to influence performance on some of the tasks in this experiment.

This study effectively demonstrates that the spatial characteristics of architectural representations in perspective displays are not always accurately perceived. There is a clear tradeoff for setting GFOV in perspective displays: A 60° GFOV is necessary for perceiving the basic characteristics of space accurately; however, if spatial orientation and representation are important, a 90° FOV or larger is required. To balance this tradeoff if symbolic enhancements are included in the virtual environment, such as VM techniques, larger FOVs are less of a concern.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my mother, Audrey Alice Neale, for the love, guidance, and support she has provided me with throughout my life. Without her unconditional belief in my abilities, this project could not have been possible.

I also owe a great thanks to my wife, Vicki Lewis-Neale, for the love, patience, understanding, and help she has provided me with over the duration this project.

I would like to thank Dr. Robert C. Williges for the guidance and insight he has provided towards the completion of this thesis. His patience was vital to the successful completion of this work. I would also like to thank the committee who served on this project, Dr. Walter W. Wierwille and Dr. Albert M. Prestrude, for their suggestions and help in completing this thesis.

TABLE OF CONTENTS

TITLE PAGE	i
ABSTRACT	ii
ACKNOWLEDGMENTS	iv
TABLE OF CONTENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
INTRODUCTION	1
Perspective Displays.....	5
Viewing parameters used to generate perspective displays.....	8
Perceptual errors in computer generated imagery	12
Perspective display enhancement techniques	19
Field-of-view	21
Field-of-view: real-world	21
Field-of-view: stereoscopic displays	24
Visual Momentum	28
Spatial Orientation.....	37
Landmarks in cognitive map building	40
Spatial orientation in virtual environments.....	41
Integration of Issues	43
Purpose	47
METHOD	50
Experimental Design	50
Dependent Variables	53
Subjects.....	54

Materials and Apparatus.....	55
Vision tests	55
Spatial abilities tests	55
Computer	56
Virtual environment application	56
Virtual environment.....	57
Procedure.....	62
Prescreening and training	62
Room dimension estimates	63
Direction judgments	63
Distance estimates	64
Cognitive map task	64
Room reconstruct task	65
Questionnaire responses	66
RESULTS	67
Analysis on Space Dimension Judgments.....	70
Analyses of room dimension estimates	70
Analyses of distance estimates	74
Analysis on Spatial Orientation Variables	79
Analyses of cognitive map scores.....	80
Analyses of direction judgments	83
Analysis of object placement error for the room reconstruction task	87
Analysis of room reconstruct time.....	89
Analysis of Questionnaire Responses	91

Analysis of Correlations	99
DISCUSSION	102
Performance with Basic Space Dimensions	102
Room size estimates	102
Distance estimates	105
Spatial Representation and Orientation	108
Distance estimates	108
Cognitive map	112
Direction judgments	113
Room reconstruct error	115
Future Research	117
Conclusions	119
REFERENCES	125
APPENDIX A: Post-test Questionnaire	133
APPENDIX B: Introduction to the Study	135
APPENDIX C: Participant's Informed Consent	138
APPENDIX D: General Instructions	142
APPENDIX E: Verbal Instructions	145
APPENDIX F: Additional Results of Statistical Analysis.....	147
VITA	155

LIST OF TABLES

Table:

1. Treatment order for the within-subjects factor	51
2. ANOVA summary table for room size estimates	70
3. ANCOVA summary table for room size estimates	71
4. ANOVA summary table for distance estimates	74
5. ANCOVA summary table for distance estimates	75
6. ANOVA summary table for cognitive map score	81
7. ANOVA summary table for direction judgments	83
8. ANOVA summary table for object placement error	87
9. ANOVA summary table for object placement time	89
10. ANCOVA summary table for object placement time	89
11. ANOVA summary table for question 1	91
12. ANOVA summary table on question 6	93
13. ANOVA summary table for question 7	95
14. ANOVA summary table for question 8	96
15. ANOVA summary table for question 9	98

LIST OF FIGURES

Figure:

1a. Conventional display	7
1b. Perspective display	7
2. Representation of the 2D projection arising from 3D images	9
3. Top-down view of an observer viewing a perspective display with the eye placed at the station point.....	11
4. Visual momentum's relationship to mental effort	30
5. Techniques to increase visual momentum.....	31
6. 3 x 2 x 2 mixed, factorial design	50
7. Floor plan for the simulated office building.....	58
8. Sample view outside room G in the VE	59
9. Floor plan for the simulated office building with landmarks only	60
10. Floor plan of VE room for reconstruction task	60
11. VE room for reconstruction task	61
12. Overall mean room size estimates for VM.....	72
13. Overall mean room size estimates for FOV	72
14. Interaction between VM and FOV for room size	73
15. Mean distance estimates for FOV	76
16. Mean distance estimates for VM.....	77
17. Interaction between difficulty and VM for distance estimates.....	78
18. Interaction between difficulty and FOV for distance estimates	79
19. Overall mean map scores for VM	82
20. VM x FOV interaction for the cognitive map scores	82
21. Mean degrees azimuth direction judgments for difficulty	84

22. Mean degrees azimuth direction judgments for VM.....	85
23. Interaction effect for difficulty x VM.....	86
24. Mean object placement error for FOV	88
25. Mean time to reconstruct the room layout for VM.....	90
26. Mean ratings for question 1	92
27. Mean ratings for the FOV main effect on question 6.....	94
28. The VM x FOV interaction for question 6	94
29. Means for the VM main effect on question 7.....	96
30. Means for the VM main effect on question 8.....	97
31. Means for the main effect of VM on question 9	98
32. VM x FOV interaction for question 9	99

INTRODUCTION

Increasingly, computer displays are being used as the interface "window" between complex systems and their users. In addition, it is becoming more common to see computer interfaces represented by spatial metaphors, allowing users to apply their vast prior knowledge and experience in dealing with the three-dimensional (3D) world (Wickens, 1992a). Evidence supporting the utility of such interfaces can be seen by the proliferation of the graphical user interface (GUI) (pronounced "gooey"). The GUI is characterized by a graphical display that has windows, buttons, boxes, icons, et cetera (Hix and Hartson, 1993). Typically, the GUI is a flat workspace represented by a "desktop" metaphor. The desktop, which has been the dominant interface metaphor since the 1980s used on systems like the Apple Macintosh[®], represents the computer display as a desk top environment where users can manipulate objects. The GUI approach to human-computer interaction is in sharp contrast to the "conversational" command line interaction that existed prior to 3D metaphors (Ellis, 1991).

The GUI, a spatially guided representation and interaction, is referred to as a direct manipulation interface (DMI). Users point-and-click on objects to perform actions in the display space. DMIs are intuitive because they allow users to interact with the computer in ways that are analogous to how people interact with objects in the real-world (Hutchins, Hollan, and Norman, 1985). Although the intuitive value of the visual-spatial metaphor seems evident, there has not been a great deal of empirical investigation demonstrating its merit. Furthermore, Shneiderman (1993), who has been a strong proponent of DMIs, cautions that the meaning of visual-spatial

computer interface representations may be ambiguous and misunderstood by users.

The virtual environment (VE) is an extension of the desktop metaphor to the full environment of the real-world. VEs have also been referred to as virtual reality (VR), artificial reality, synthetic environments, cyberspace, and virtual worlds. Although there is not a large body of research which has substantiated the usefulness of 3D metaphors, anecdotal reports and related human-performance studies suggest that VE, 3D systems could become the future of human-computer interaction.

Norman (1988) points out that many computer systems are inherently difficult to use because system operations are not visible to the user. Furthermore, it has been demonstrated that information can be encoded and discriminated more effectively when it is represented by multiple dimensions (Miller, 1956). VEs by their very nature provide information in multiple dimensions and have the potential for making system operations perceptible and accessible to the user. VEs give promise for optimizing the match between computer display technology and the human's perceptual, cognitive, and motor capabilities. The naturalness of this coupling between the human and machine will enhance the communication channel between the two and reduce the cognitive effort required of the user. However, "Optimization of the design of interactive instruments using pictorial formats requires an understanding of the manipulative, perceptual and cognitive limitations of human viewers" (Ellis, 1993).

The need for understanding the human's limitations and requirements makes virtual environments the perfect topic of study for human factors

professionals (Thomas, 1992). Furthermore, Wells (1992) claims that the implementation of VR is the "...ideal niche for human factors engineers..." because of the human considerations imposed by VR technology.

The VE has the potential to become an historical lever as significant as the printing press and computer, not because it will be a useful tool for completing practical tasks, but because the virtual world will change the way in which people view the real-world (Rheingold, 1990). VR has many different meanings depending on whom you ask. Many people associate VR with specific devices, such as head-mounted displays (HMDs), data glove input devices, and 3D audio. Others have extended the meaning to include such things as books, movies, or fantasy and imagination. Wells (1992) defines VR as "... a computer-generated environment which is sometimes synthetic, in which a person can interact with portrayed entities." In general this definition is useful because it restricts VR to computer-generated VEs without reference to specific technologies or to the level of system fidelity. Essentially, VEs are interactive computer-simulated environments which can provide visual, auditory, and other sensory inputs that can be explored freely in real time, characterizing a world inside the computer.

Distinguishing VE systems by the mode in which they interface with the user can often be a helpful distinction for understanding and defining what VEs are and the sense of presence that can be experienced in them. Isdale (1993) provides several useful distinctions: Desktop VR or window on a world (WoW), as it is sometimes called, uses a conventional computer monitor to display the VE. The display applies perspective geometry to provide the illusion of 3D space. Much of the success in this area of VEs is

based on advances in computer graphics and on the increased processing power of low-end computer workstations.

Fully "immersive" VE systems have been given a great deal of attention by the media recently. Although these systems can range in the hundreds of thousands of dollars, their capabilities have often been greatly sensationalized and exaggerated. Nevertheless, they can be very impressive in terms of immersing the user and providing a sense of presence in the VE. These systems use HMDs which present visual and auditory signals through miniaturized equipment. A glove placed over the hand is often used as the input device to manipulate objects in the VE, which is equipped with sensors on the fingers. HMDs and input gloves usually contain overall position/orientation tracking technology which provides 6 degrees-of-freedom tracking position for the head and hand. Between the extremes of desktop and fully immersive VEs are a range of hardware and software configurations that create different levels of fidelity for experiencing VEs.

One important concept that needs to be defined to help fully grasp the general nature of VEs is the distinction between egocentric and exocentric frame-of-reference or viewpoint. Virtual spaces can be viewed from either egocentric (inside-out) or exocentric (outside-in) perspectives. From an egocentric perspective, the environment is experienced from the actual viewpoint assumed by the user, and the user perceives that their viewpoint is from within the environment. Exocentric viewpoints are from positions other than those assumed by or represented as the user. For example, the user's position, and therefore viewpoint, can be represented as a symbol in the VE. The egocentric, inside-out viewpoint is more realistic because it

corresponds to the viewpoint assumed by humans in the real-world. The type of viewpoint afforded to the user can have two important effects on performance in VEs. First, the frame-of-reference determines the types of movements that a user has to make to track a visual target. Compensatory tracking is required from egocentric viewpoints, and pursuit tracking is required from exocentric viewpoints (Ellis, 1991). The type of human tracking behavior that the user exhibits can have a large effect on movement through the VE. Secondly, viewpoint can play an important role in how users build a mental model of the VE, affecting orientation and navigation.

Perspective Displays

Object-centered cues (characteristics of objects in the world) and observer-centered cues (characteristics of the visual system) allow us to perceive 3D space. Perspective displays create the illusion of three dimensions through the use of object-centered cues: linear perspective, interposition, height in the plane, light and shadow, relative size, textural gradients, proximity-luminance covariance, aerial perspective, and relative motion gradient or parallax. Observer-centered cues, such as binocular disparity, convergence, and accommodation are more associated with 3D stereoscopic displays (see Wickens (1992a) for a full explanation of these cues).

Three-dimensional perspective displays are essentially conventional monitors using perspective geometry to create the illusion of 3D space. However, although 3D perspective displays do not afford viewers observer-centered cues, they can be very effective in causing people to perceive that they are viewing a realistic scene in three-dimensions. Three-dimensional

imagery representing a real-world scene is more intuitive when the tasks required of the user have 3D spatial relationships. Referring to a screen as a 3D perspective display is somewhat of a misnomer because monoscopic perspective displays, which project the image in perspective to the eye, cannot truly present information in three dimensions. Therefore, the illusion of depth produced by these displays is sometimes referred to in the literature as two-and-a-half-dimensional (2 1/2D). Although perspective displays will be referred to here as 3D displays, it is important to note that, because the image is not being displayed stereoscopically, perspective displays are not truly 3D displays. However, it is common in the literature to see perspective imagery referred to as 3D.

Desktop VEs are depicted on 3D perspective displays. Information can be presented on 3D (perspective and/or stereoscopic) displays versus a two-dimensional (2D) planar, conventional display. With 2D displays, only the x and y axis of the three dimensions of space are represented. The third dimension (z axis) must be encoded with shapes, numbers, colors, and so forth (McGreevy and Ellis, 1991). In contrast, perspective displays present information without collapsing the vertical dimension. Representing 3D information in the two contrasting formats can have a dramatic effect on the quality of the information being communicated. Figures 1a and 1b represent a cube being depicted in the conventional versus perspective views. The height of the cube in the conventional display is represented by a vertical bar to the left of the cube. The laborious mental reconstruction required to extract the spatial information from Figure 1a, and the almost intuitive nature in which the spatial information is being communicated from Figure

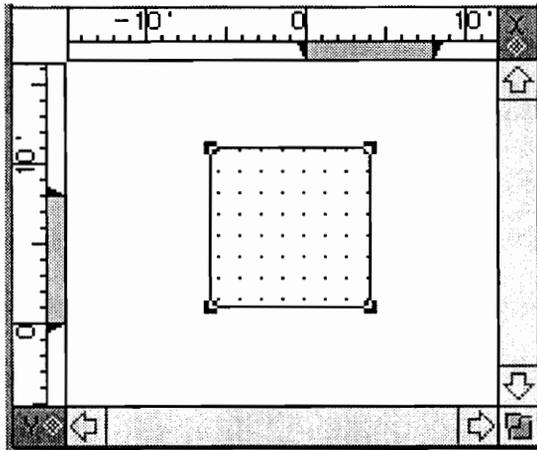


Figure 1a. Conventional display.

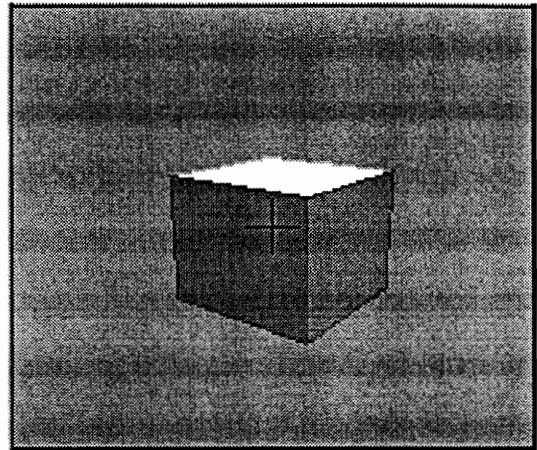


Figure 1b. Perspective display.

1b, suggest that there are significant advantages to presenting 3D information spatially.

Several experimenters have demonstrated the advantages of using perspective over conventional displays. Bemis, Leeds, and Winer (1988) compared pilot performance on a conventional versus perspective display. Pilots were required to search the display, detect any threats, and determine the nearest interceptor, which was the closest friendly aircraft to the threat. The results of this experiment showed that significantly fewer errors were made with faster response times when the perspective display was used. Ellis and McGreevy (1983) tested pilots' avoidance maneuvers while different cockpit air-traffic displays were used. They found that a perspective display had significant advantages over a conventional display, which was indicated by the doubling of vertical maneuvers made by pilots, resulting in greater separation between aircraft. Wickens and Todd (1990)

reported results from a study which partially support the argument that 3D perspective displays provide objectness and three dimensionality, not afforded by two-dimensional displays. Information presented in multiple dimensions can facilitate tasks requiring greater integration of the information.

Furthermore, Kim, Ellis, Tyler, Hannaford, and Stark (1987) performed two experiments to compare the performance between a perspective and stereoscopic display in three-axis manual tracking tasks. The results indicated that when a perspective display is used with optimal perspective parameters and is enriched with visual enhancements, tracking performance can be equivalent to that of a stereoscopic display.

Viewing parameters used to generate perspective displays. In perspective displays, 3D information is projected onto a 2D, flat surface (display screen). A number of parameters define the type of planar projection that is created, and their manipulation can have substantial effects on the perception of the depicted images. Figure 2 characterizes the stimulus geometry used to display images on the screen. Every point in the 3D scene is projected to the station point or what is commonly referred to as the center of projection. The projectors originate from the stimulus images, intersect with the picture plane, and then are projected to the station point. The window is that part of the picture plane which is bound by the virtual space. The size and shape of the window determine the size and shape of the information that is available at the station point. However, the viewport is that part of the monitor in which the image is mapped. In other words, the

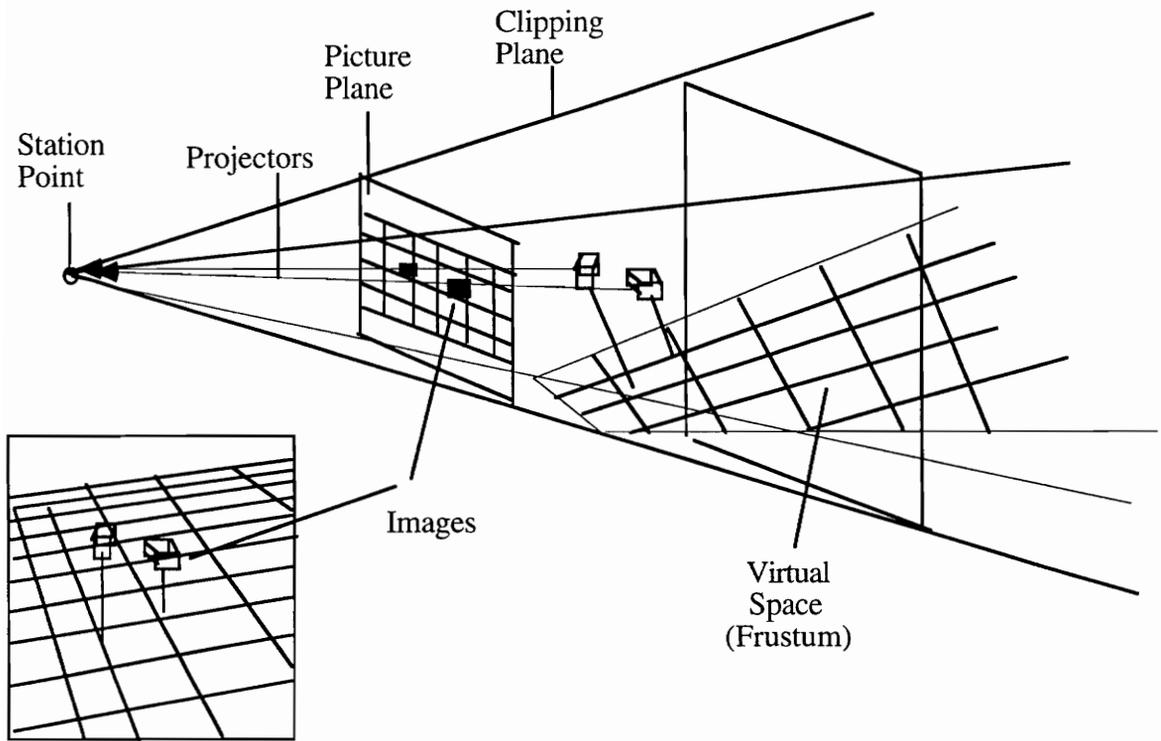


Figure 2. Representation of the 2D projection arising from 3D images.

viewport is the visible region of the screen, but the window determines the amount of virtual space that is available.

When dealing with computer displays, field-of-view (FOV) can have different conflicting meanings. FOV in the real-world is the visual angle of the scene (world) subtended at the observer's eye. Geometric field-of-view (GFOV) is the FOV that is visible in the virtual world. GFOV is the visual angle of the virtual scene subtended at the computer's eye (station point). For perspective displays, GFOV is the width and height subtended by the virtual world given as a visual angle in degrees of azimuth and elevation. This angle is determined by the width and height of the virtual world

projecting onto the window and the distance of the station point from the virtual image.

There are four clipping planes and one hither clipping plane which determine the visible volume of virtual space and which together comprise the frustum (truncated pyramid). The clipping planes determine the boundaries for displayed and undisplayed images. The clipping planes together with the hither clipping plane, which lies in the same position as the picture plane truncating the pyramid, create the visible volume of space. The apex of the pyramid created by the four clipping planes is located at the station point. The shape of the frustum, determined by the angles in azimuth and elevation of the virtual space, determine the GFOV and is the angle subtended at the station point.

For egocentric tasks, the observer's virtual viewpoint is usually placed at the beginning of the monitor surface. The viewing angle (FOV) for the observer is based on the width and height of the display viewport (visible image on the screen) and the observer's distance from the display. Figure 3 illustrates the relationship between the GFOV and the observer's viewing angle (FOV). Only when the angles between the GFOV and the viewing angle are equal is the observer's eye at the station point. The GFOV angle and station point are independent of where the observer's eye is located; in other words, the observer's eye can be positioned in front of or behind the station point. However, the station point is dependent on the GFOV and vice versa. In the real-world under normal viewing conditions, viewing angle and FOV are equivalent, and the capabilities of the peripheral vision system determine its boundaries. It is important to point out that FOV and

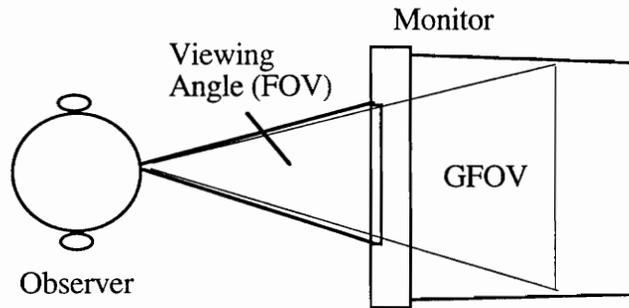


Figure 3. Top-down view of an observer viewing a perspective display with the eye placed at the station point.

GFOV, although different constructs, are considered conceptually and theoretically to be equivalent for the purposes of this research. In other words, restricted GFOV in VEs is assumed to produce similar consequences as restricted FOV in real environments. It is interesting to note that although the GFOV is the FOV for the virtual world, the observer's peripheral FOV still extends into the real-world.

Many of the applications which allow the development of virtual spaces for perspective displays contain a "synthetic camera" that provides the GFOV angle into the VE. Changes in the "synthetic lens" zoom between wide-angle and telephoto settings. These settings are used to manipulate the GFOV in the VE, which will also change the distance of the station point from the virtual image. Moreover, changes in the GFOV (lens settings) will also change the distance of the station point from a stationary observer's eye position. Recall that the observer's viewing angle and the GFOV (station point) are independent of each other. This situation is analogous to the camera-to-observer distance equaling the viewing angle and the camera-to-image (lens setting) distance equaling the GFOV. What is uniquely different

between the synthetic camera and a real camera is that objects can be scaled selectively in the VE as a function of perspective, which can not be done in the real-world. Because of the inherent limitations in the human's ability to reconstruct 3D images from a 2D surface, and because of the ability to manipulated scale via perspective, perceptual errors occur while viewing perspective displays.

Perceptual errors in computer generated imagery. Several experimenters have noted that the perception of depth in pictorial representations—pictorial representations contain the same depth cues as perspective displays—is inferior to that of the 3D real environment (Deregowski, 1972; Gibson, 1969; Wilcox and Teghtsoonian, 1971). One explanation that could account for this is that the observer receives conflicting cues about the depth in the scene. While several observer-centered cues indicate the picture surface is flat, other object-centered, perspective geometry cues convey 3D depth from the scene.

Three-dimensional computer generated displays create images composed of lines and/or polygons. These images can lack significant detail when compared to the real-world. Because these 2D images must be mentally reconstructed into 3D representations, errors can result because of incorrectly choosing the relevant viewing parameters (Grunwald, Ellis, and Smith, 1988). Systematic errors in size and distance judgments can occur in perspective displays (Roscoe, 1984). Framed versus unrestricted visibilities were compared by having participants respond nearer or farther using the psychophysical method of constant stimuli. Participants repeatedly judged the distance to be shorter, indicating that a perceived minification in the

computer generated image resulted. And these errors were found to be slightly greater viewing images through a framed windshield rather than with unrestricted visibility. Roscoe (1984) points out that viewing images on a screen is essentially monocular as compared to binocular viewing in the real-world or with stereoscopic displays. This results in the elimination of binocular parallax used for distance judgments.

A series of experiments has demonstrated that observers exhibit a systematic bias in judgments made with perspective displays as a result of the misinterpretation of the viewing parameters used to create the 3D images (Ellis, Smith, and Hacisalihzade, 1989; Grunwald and Ellis, 1986; McGreevy and Ellis, 1986). In fact, the appearance of the same scene can look very different depending on the computer graphic parameters used to generate the image. These errors can result as a function of how the GFOV is generated in the perspective display.

McGreevy and Ellis (1986) had subjects judge the direction of targets in relation to a reference object shown on a perspective display with four levels of GFOV (30°, 60°, 90°, and 120°). This was accomplished by setting a synthetic camera lens at four different distances from the images. GFOV had a significant effect on direction judgment errors in azimuth and elevation. The magnitudes of the errors were a function of the direction of GFOV change. Target elevation was overestimated in all the conditions, and it increased as the GFOV increased, which resulted from a telephoto effect. A sinusoidal azimuth error in direction judgment occurred as a function of the azimuth direction of the target. This relationship revealed that targets were judged to be farther to the left or right of the reference object than they

actually were; however, the errors in one extreme GFOV gradually changed as the GFOV moved to the other extreme. When the reference grid is broken into four quadrants, azimuth error changes sinusoidally as the target moves clockwise or counterclockwise through the quadrants. The whole pattern of sinusoidal errors reverses (flips) as the GFOV is moved from one extreme to the next.

These findings demonstrate two important causes of exocentric direction judgment errors in perspective displays: 1) errors in direction are a function of the actual direction of targets being judged, and 2) direction errors arise as a function of the perspective parameters used to generate the display, in this case, GFOV. The perceptual biases just described have been labeled respectively the "3D-to-2D projection effect or "2D effect" for short and the "virtual space effect." The 2D effect resulting in a sinusoidal azimuth error, which depends on the viewing quadrant of the target and on the GFOV, decreases in amplitude as the GFOV angle increases. This problem is a generalization of slant overestimation of a surface (Perrone, 1982; Sedgwick, 1986).

The virtual space effect results from an inappropriate viewing distance between the eyes and the monitor surface. This situation occurs when the GFOV is manipulated, resulting in the station point moving accordingly, but the observer's eye position does not change. When the eye point and the station point are not perfectly aligned, perceptual biases result in the perceived location (direction and distance) of the images caused by the magnification (narrow GFOV) or minification (wide GFOV). McGreevy and Ellis (1986) have referred to the observers' behavior caused by the

virtual space effect as the "window assumption." In this assumption, the observer erroneously assumes that his viewpoint is at the correct geometric station point, and therefore that the projectors from the image are straight. However, when the eyes are not at the station point, the projectors are, in effect, bent at the point where they reach the display screen. The amount of bend is determined by the amount of misalignment between the eyes and station point. What is interesting is that the amplitude of this bias increases as the GFOV increases.

In summary, the perceptual errors caused by the 2D effect decrease, and the errors caused by the virtual space effect increase as the GFOV increases. These findings demonstrate that the amplitude of the azimuth error for exocentric direction judgments occurs the least with a 60° GFOV. The magnitude in perceptual errors increases as the GFOV moves in either direction away from 60° with narrower and wider GFOVs. Perceptual errors are caused by the 2D effect at the narrow GFOVs, and the virtual space effect causes perceptual errors at the wider GFOVs. Barfield, Lim, and Rosenberg (1990) also had observers perform exocentric azimuth judgments and found that 45° and 60° GFOVs resulted in optimum performance. These optimal GFOVs being suggested by this research involve stimuli being presented from an exocentric viewpoint which then required an exocentric judgment. In other words, the relative direction between two objects presented on the screen were being judged.

A similar pattern in perceptual biases for judgments of target azimuth was found in an experiment which also had subjects determine the direction of a target in relation to another object (Grunwald and Ellis, 1986). In this

study the experimenters controlled for the virtual space effect by keeping the observer's eye at the center of projection or the station point throughout the experiment. Again, it was shown that the observers revealed perceptual biases as though they were looking through a telephoto lens. Although the experimenters modeled these errors very differently from the biases assumed to have caused the virtual space effect, direction judgment errors were shown to be the smallest when the observers viewpoint (eye position) was behind the geometrically correct center of projection.

To compensate for the perceptual biases that were found to exist in perspective displays, a model was developed that makes compensatory distortions systematically in the parameters used to formulate a perspective display (Grunwald, Ellis, and Smith, 1988). The model to explain the 2D effect suggests that observers are making errors because they are basing their judgments on the spatial relationships from the projected image rather than accurately reconstructing the original 3D relationships. The virtual space effect model predicts that because observers are not viewing the display from the correct center of projection, they are reconstructing a distorted 3D space.

Grunwald and Ellis (1988) have summarized two design solutions for the implementation of perspective displays:

- 1) The correct center of projection (station point) should be placed in front of the observer's eye position as a result of the telephoto bias. In other words, a wider GFOV should be used than is necessary to acquire the correct viewing geometry.

- 2) The real-time interactive incorporation of motion should compensate considerably for the perceptual biases indicated as the result of motion or gradient parallax.

What clearly stands out from the discussion of perceptual errors with computer generated imagery is that there has been a consistent systematic telephoto bias that occurs while making judgments about the spatial relationships of images in perspective displays. However, what is not so clear is whether the findings that azimuth errors as the result of absolute target location and GFOV, which are presented in an exocentric framework requiring an exocentric judgment, will extend to egocentric perspectives and judgments.

One study which helps to clarify this issue was conducted by Dorigi, Ellis, and Grunwald (1993). The spatial situational awareness of pilots was measured to see if having a perspective flight pathway display integrated with an electronic map affected pilot performance. The "Tunnel-in-the-Sky" perspective display provided an egocentric (inside-out) frame-of-reference, while the electronic map provided a exocentric (outside-in) reference frame. Situational awareness for this environment required pilots to integrate information from the two displays, which was then used to make an egocentric judgment (judgment of visual direction to targets along an approach path). The azimuth angle of visual direction to target location was significantly underestimated. This study illustrates that, even when egocentric and exocentric frames-of-reference are combined, egocentric judgment errors can still persist.

Furthermore, Ellis, Smith, and Hacisalihzade (1989) found that egocentric judgments made from an exocentric viewpoint also resulted in direction judgment errors. Subjects were required to indicate a target location by adjusting a head-mounted cursor. This is an egocentric task which involves making a judgment about target location in relation to one's own visual direction, based on an exocentric viewpoint of target direction presented on a perspective display. Subjects' misinterpretation of the viewing parameters on the perspective display caused an overestimation in subjects' visual gaze direction.

All the studies discussed thus far about azimuth direction errors contain perceptual biases, in one way or another, that presented stimulus objects from an exocentric viewpoint. Regardless of the variations in egocentric and exocentric viewpoints and tasks, however, errors have persisted. The scenario which has yet to be described is whether an egocentric viewpoint or reference frame from within the VE will lead to a biased egocentric perceptual judgment also made from within the VE. In addition, the majority of studies presented in this discussion have not involved the dynamic interaction that occurs when motion is introduced, which is expected to greatly reduce the types of perceptual direction biases that transpire with perspective displays.

Brickner and Foyle (1990) looked at restricted GFOV in head-down and head-up 19" perspective displays for a simulated helicopter maneuvering task. Three GFOV angles were examined: 25 x 19, 40 x 30, and 55 x 41 (degrees azimuth x degrees elevation). Pilots were required to maneuver through a slalom course consisting of pylons. As the GFOV became more

restricted, pilots were unable to modify their flying strategies, and as a result, flew closer to the pylons, hitting the pylons significantly more often. These researchers interpreted the findings to suggest that the participants perceived the display as the entire world versus a restricted window into the world. This hypothesis, if true, has important implications for the design of virtual environments because a restricted GFOV may not only effect performance, but it may also affect people's cognitive model of the virtual world.

Perspective display enhancement techniques. Several researchers have tried to reduce the perceptual biases in perspective displays by providing geometric and symbolic enhancements to the interface. Ellis (1993) maintains that there are many kinds of geometric enhancements for spatial displays, "...but their common feature is a transformation of the metrics of either the displayed space or of the objects it contains." Basically, this means that there is a deliberate spatial distortion of the image to compensate for perceptual biases and improve the precision of the information that is being displayed. Symbolic enhancements, on the other hand, include things, such as objects, scales, or metrics which add additional information to facilitate communication of the spatial information being presented.

One geometric enhancement that has been suggested by several researchers is the introduction of a wide-angle distortion to compensate for the telephoto bias known to exist in perspective displays (McGreevy and Ellis, 1986; Grunwald and Ellis, 1987; Roscoe, 1984). Also, the use of stereopsis can improve the perception of depth and reduce the bias in

perspective displays (Ellis, Tharp, Grunwald, and Smith, 1991). Dynamic interaction with the virtual environment (e.g. motion) can also eliminate biases experienced in perspective displays.

Several types of symbolic enhancements have been demonstrated to be very effective in reducing perceptual biases in perspective displays. The use of 3D objects whose shape characteristics are known *a priori*, such as size, shape, and parallelism or perpendicularity of lines can provide cues for spatial orientation (Grunwald and Ellis, 1986). Familiarity cues can help the observer estimate the 3D orientation of an object from a 2D projection. The use of reference grids and posts connecting objects to the grid to indicate object location and orientation have been shown to alleviate perceptual biases (Ellis, McGreevy, and Hitchcock, 1987). In addition, compass roses have been used as symbolic enhancements for optimizing azimuth estimation in perspective displays (Ellis and Hacisalihzade, 1990). These enhancements consist of a compass like device that is divided into different densities and superimposed on a ground reference grid and/or on a response dial. The compasses are used to provide reference angles when making azimuth judgments in perspective displays. Exocentric azimuth judgments were shown to significantly improve as a result of these symbolic aids. Barfield, Lim, and Rosenberg (1990) used the ability to rotate the perspective scenes and solid shaded objects in the scenes as visual enhancements. The ability to rotate the scene significantly improved the accuracy of judgments for object elevation.

Lastly, in a different approach to reduce perceptual biases found in perspective displays, Tharp and Ellis (1990) demonstrated that training could

reduce, but not eliminate, errors for exocentric direction judgments. The training included presenting error feedback after a direction judgment was made by displaying an object in the judged position to that of the true position of an object. Using this method, observers continued to learn until the amplitude of the error asymptoted at about 33% of the baseline; however, it was clear that the error would not go to 0 with the training method alone. These methods clearly demonstrate that visual enhancements can reduce, if not eliminate, the perceptual biases which are manifested in perspective displays.

Field-of-view

With recent advances in display technology and computer processing outputs, information is increasingly being presented on 3D (perspective and/or stereoscopic) displays where FOV/GFOV can be manipulated. Because of practical limitations in the implementation of the hardware, and limitations in processing speeds demanded by large FOVs, 3D computer representations often restrict the FOV/GFOV without consideration for the consequences on users' performance. Studies evaluating restricted FOV in the real-world are helpful for understanding problems that can arise in VEs.

Field-of-view: real-world. In the real-world, the maximum normal achromatic binocular field-of-view (FOV) for the visual system is approximately $\pm 100 \times \pm 60$ (degrees azimuth x degrees elevation) (Boff and Lincoln, 1988; Harrington, 1964). This visual field is comprised of an irregularly shaped ellipse created from the overlapping monocular FOVs of both eyes.

Much of the visual adaptation research, where observers look through spectacles which alter their visual field, has often severely restricted the FOV of participants without consideration for its impact on performance. Dolezal (1982), while trying to identify the confounding effects of restricted FOV on adaptation research, wore two paper tubes for 6 days, restricting his visual angle to 12° horizontal x 11° vertical. Dolezal's study had several consequences on his ability to perceive and interact with his environment: During head movements, the FOV appeared to sweep over the environment. In addition, head movements had to be substituted for large eye movements. With a normal FOV, much of the visual information is shared from one head movement to the next. With a restricted FOV, however, successive head movements have little or no information in common. Continuity of the visual world depends on the overlap of information across successive FOVs. In fact, reducing the peripheral vision, reduced the amount of information necessary for effective orientation and locomotion.

The restricted FOV had two consequences: 1) the amount of peripheral information was reduced, and 2) the overlap of information was reduced between successive FOVs. One of the most significant findings of Dolezal's experiment was that his ability to develop a cognitive map of unfamiliar places was severely impaired. As a result, he had difficulty orienting himself in unfamiliar spaces. In addition, the orientation of objects in places was also misjudged. Dolezal (1982) states that, "The perception and hence conception of the visual world is evidently dependent upon the size of the FOV..." This lack in the ability to maintain orientation and

develop a cognitive map of the surroundings resulted in the inability to understand the meaning of ongoing events.

Lastly, the restricted FOV also resulted in size and distance underestimation, causing objects to appear nearer and smaller. One plausible explanation given is that because the visual scene is deprived of context, the observer is only able to base size and distance judgments on retinal image size.

Hagen, Jones, and Reed (1978) looked at the perceptual effects of restricted FOV for estimating size and distance in pictorial representations. Observers viewed stimuli under four different monocular conditions: unrestricted monocular view, peephole view, view bounded by a rectangular frame, and stimuli viewed on photographed slides. Subjects were required to scale the size and distance of triangles at different distances. The results illustrated that, in all of the truncated FOV conditions, observers experienced a compressed distance perception. The experimenters concluded that the size and distance compression was due to the lack of visual information available in the foreground from the observer to the visual scene. The truncation in the foreground of the FOV compressed the size and distance perception producing a telephoto effect. The experimenters hypothesized that, because of the lack of foreground distance information, participants added a small fixed value to all of their distance judgments. These results support the argument that photographs, and therefore 3D perspective displays, can result in size and distance distortion.

To examine the role of restricting the FOV on perceptual and performance effects for forming a cognitive map, Alfano and Michel (1990)

truncated the FOV of observers to 9°, 14°, 22°, and 60° using vision goggles while they examined a room that was previously unseen. For the cognitive map task, there was also a control group that viewed the room with a normal FOV. An 11 x 19 foot room was furnished with common items, such as chairs, bookcase, lamp, et cetera. Participants were allowed to scan the room for 60 seconds, and then were required to recreate the layout of the room on a two-dimensional floor-space representation. Accuracy for recreating the spatial layout, by placing items on the layout representation, was significantly affected by the degree of restriction in the FOV. Post-hoc tests revealed that the 9° and 14° FOV conditions failed to place as many items as the full FOV group. Also, the greater the truncation in the FOV, the fewer items that were replaced for each successive restricted FOV condition. Following up with a post-test interview, 82% or better of the participants in all of the restricted FOV conditions responded that they had perceived the room to have changed appearance in size (larger or smaller) when they revisited the room with an unrestricted FOV.

Many of the results being discussed suggest that the peripheral information available in large FOVs, and its overlap, are necessary to enable humans to construct an accurate representation of their environment. And that accurate representation of one's surroundings is necessary to perform spatial orientation tasks effectively.

Field-of-view: stereoscopic displays. Much of the research conducted in the real-world on FOV has been concerned with how the visual system uses peripheral vision, not only for spatial orientation, but also for visuomotor activities like walking and reaching for objects. Recently with

the advent of VR technology, humans are experiencing interaction with analog computer representations which provide them with simulated 3D environments. Because these computer-simulated 3D representations often fall short of accurately depicting the real-world, and because of other limitations of the technology, like how users navigate in VE spaces, restricted FOVs in simulated spaces place even greater demands on the spatial orientation ability of users. Wells, Venturino and Osgood (1988) compared the performance of participants under various different size FOVs using the Visually Coupled Airborne Systems Simulator (VCASS), which utilizes head-mounted VE technology. One of the important issues under consideration in this research was the degree of spatial awareness experienced, measured by the degree to which stationary targets could be acquired, memorized, and then recalled. Recall was tested by a replacement procedure that required participants to point to the location of previously memorized targets once they had been removed, using the cross hairs on the display. The trigger on a joystick was then used to replace the items in their original position. Search time was shown to be sensitive to FOV manipulations. Increasing search times accompanied decreasing FOVs. The explanation given for this discovery was that finding and then re-finding targets was impaired because of memory demands placed on participants. However, replacement error for the targets was unaffected by FOV. The findings suggest that once the targets were acquired and memorized, recall and replacement was not impaired by restricted FOVs.

Further data analysis on this experiment (Venturino and Wells, 1990) revealed that FOV significantly increased not only the number of head

movements, but also their velocity. Fewer, but faster, head-movements were found with larger FOVs. Not surprisingly, there was a correlation between time to acquire and memorize target locations and head movement. As the FOV was increased, subjects required less time for acquiring and memorizing target position, resulting in fewer head movements. One interesting finding is that when a terrain versus a blank background were compared, participants appeared to be matching targets with terrain features, which was indicated by slower head movements and a greater recall for target positions in the terrain condition over the blank background.

In two follow-up experiments, Venturino and Kunze (1989) looked at the ability of participants to acquire, memorize, and recall the location of targets in a VE using a HMD. In addition, they manipulated memory load by varying the number of targets presented. The two experiments were identical except for the number of targets removed during the replacement phase. In the first, all of the targets were removed, and in the second, only the targets to be replaced were removed. Spatial cognition was again assessed by the target replacement procedure. There were five levels of FOV ranging from 20 x 20 to 90 x 60 (degrees azimuth x degrees elevation) and three levels of target memory load (3, 6, and 9). In both experiments search time to acquire targets was significantly affected by the FOV afforded to the observer. The smaller the FOV, the more time it took to acquire the information. Restricted FOVs impede the ability of people to acquire spatial information, and it requires a greater degree of spatial information integration in developing a cognitive map of the environment. The additional burden of integrating spatial information in restricted FOVs

places greater demands on head movements, memory, and attentional resources. Even though the number of targets did reduce participants' spatial memory, as in the Wells et al. (1988) study, FOV had no effect on participant's abilities to utilize their mental representation of the environment that had already been mapped into memory.

The idea that restricted FOVs place greater demands on memory and attentional process was confirmed by examining how performing a spatial cognition task under truncated FOVs also resulted in decreasing performance on a secondary task (Wells and Venturino, 1989). Again, subjects were required to acquire, memorize, and replace objects in their original position once they had been removed; however, in addition, subjects had to perform a separate tracking task. This study effectively demonstrated that there is a cost associated with decreasing the FOV. As the degree of FOV restriction was increased, performance on the secondary task decreased. This finding is important because it suggests that the decrement in performance as a result of FOV restriction is dependent on the task difficulty and/or the type of task. Because performance effects from truncated FOVs are task dependent, the integration of information from large virtual environments with many objects will undoubtedly require greater FOVs (Wells and Venturino, 1990).

Osgood and Wells (1991) had experienced fighter pilots fly simulated air-to-ground night attacks using a head-mounted display to determine the performance effects of restricting the FOV and to determine what the minimum FOV size is appropriate for HMDs. Faster target acquisition was found for larger FOVs. Based on their findings, FOVs larger than 30

degrees were significantly better for target acquisition. Wells, Venturino, and Osgood (1989) determined, based on performance in a head-mounted display, that the FOV necessary for accurate performance was dependent on task difficulty. In an air-to-air simulated combat mission, task difficulty was determined by the number of targets presented, replaced, and the number of threats facing a pilot. Twenty degrees FOV afforded adequate performance on an easy task, whereas a more difficult task required 60 degrees FOV.

Visual Momentum

In the last decade and a half, a great deal of research has gone into designing computer interfaces; however, most of this research has focused on the design of displays in the context of a single screen, not on integrating information across displays. Woods (1984) has identified a measure of across-display processing, "visual momentum," as the degree to which users can extract and integrate information across displays. Visual momentum is a principle that takes into account the human's cognitive processing mechanisms and allows this to direct the design of display systems in order that attentional resources be optimized in the human (Wise and Debons, 1987; Woods, 1984). Moreover, FOV, spatial representation and interaction, and the integration of display transitions that occur with VEs are dependent on integrating information across displays. Therefore, visual momentum techniques, which can improve across-display processing, should be very effective at alleviating many of the problems discussed in the previous sections.

The concept of visual momentum originated in cinematography (Hochberg and Brooks, 1978) and was based on the idea that how effectively

successive scenes in a motion picture are integrated depends on the degree of their overlap. From a cognitive psychology perspective, Woods extended the concept to include problems of across-display processing. Although visual momentum was a construct given its name based on its direct relationship to perceptual processing, the principle has a strong cognitive component (Woods, 1984). Wood's model considers visual momentum to be on a continuum where the cognitive coupling of successive displays extends from low (discontinuous total replacement) to high (continuous successive views). High visual momentum supports rapid extraction and integration of information, therefore, facilitating comprehension by the user. In contrast, low visual momentum results in slow, laborious extraction and comprehension of data across displays.

The mental workload required to integrate information across displays is directly proportional to the amount of visual momentum the display system supports. Mental workload can be reduced by allocating more of the task demands into the perceptual domain of human information processing. Spatial input is encoded and processed automatically and provides cues for information retrieval. As the visual momentum of a display system moves from low to high on the continuum, mental effort inversely moves from high to low (see Figure 4).

Two significant performance problems have been associated with the failure to effectively integrate data across successive display networks: "getting lost" and the "keyhole" phenomena. Getting lost in computer systems is a common experience for users. People have problems navigating

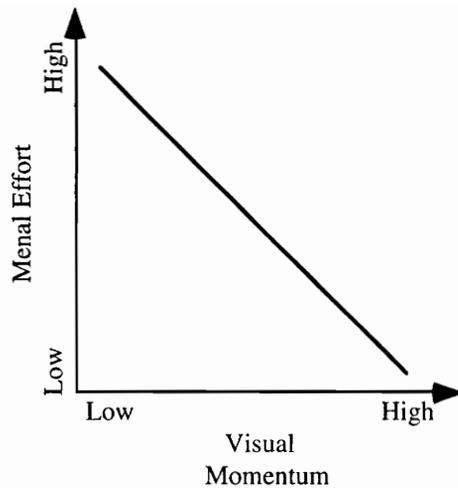


Figure 4. Visual momentum's relationship to mental effort.

in systems that have large networks of screens. Users get lost in display networks because they fail to develop a strong mental model of the system, resulting in their having a poor conception of the relationships between displays within the system. Displays often only show a fraction of the total information in a system at one time. This condition is referred to as the keyhole phenomenon. If the display structure is not well integrated, the information is presented in discrete chunks. As the integration in the display structure increases, the information flows in a more continuous manner, which is more compatible with the analog perception that occurs with spatial information.

Several additional problems in display systems can arise as a result of an increase in mental effort. Poor formulation of problem representation can significantly decrease problem-solving behavior. Memory bottlenecks can result because of a lack in system representation, affecting the ability of the user to form an accurate mental model of the system. These bottlenecks

prevent timely, error-free task completion. Degradation in attentional processes can result from focusing on particular aspects of the display information at the expense of excluding other relevant information. In summary, low visual momentum degrades users' abilities to extract and integrate information across successive displays.

Woods proposed that there are several techniques that can be used to increase visual momentum. Figure 5 lists the techniques on the continuum from low to high based on their ability to link successively viewed displays (Woods, 1984). All of the techniques in Figure 5 are intended to help the user build a spatial mental model or cognitive map of the system. The methods are intended to provide the user with perceptual cues that allow them to connect the displays cognitively.

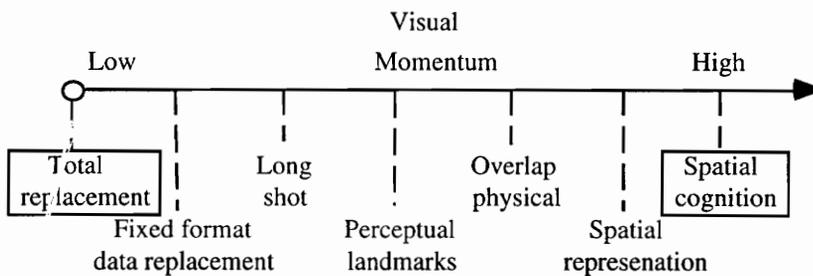


Figure 5. Techniques to increase visual momentum.

All of these techniques increase visual momentum by helping the user bridge information gaps in display transitions. They do this by providing the physical, functional, perceptual, and cognitive relationships between successive views. Spatial representation, which allows the analog representation and manipulation of information, is a very powerful method for organizing information. Spatial representation can be so compelling that

non-spatial data is often represented spatially (e.g. organizational flowcharts). Billingsley (1982) demonstrated that the pictorial representation of a hierarchical menu structure aided subjects in developing a workable mental model of how menu items interrelated. Subjects studied either a pictorial representation in the form of a memory map or a linear index of menu choice sequences. Subjects were able to find target menu items significantly faster from memory when they had received a map of the menu structure. These findings demonstrate that, by representing spatially information that has to be integrated across a series of displays, memory load can be reduced.

The spatial metaphor allows the user to visualize and move around just as they would in real 3D space. A spatial representation provides an exocentric (world centered) view of the system which in turn supports egocentric task sequences by allowing the user to maintain orientation in the system and permitting smooth transitions between tasks, information, and displays.

Four guidelines for increasing visual momentum in VEs have been summarized (Wickens, 1992a; Wickens 1992b; Wickens and Baker, in press):

- 1) Use consistency across displays. Data should be consistently represented throughout the system.
- 2) Graceful transitions should occur between displays to prevent abrupt transformation.

- 3) Anchors should be used to orient users between screen transitions. Anchors are highlighted, salient features that are invariant from one display to the next.
- 4) A continuous world map (i.e. a map representing the whole system) should be provided. The user's location in the display being viewed is always represented in the world map. This permits users to always know where their position is in regards to the system as a whole.

VEs by their very nature provide display overlap, spatial representation, and spatial cognition. The long shot and use of perceptual landmarks are not inherent in VEs. They must be designed into VEs as an additional measure to insure that the human-machine interface is optimized.

The long shot, one of the visual momentum techniques, provides an overview or "world map" of the display system. The overview map shows the relationships between the information or displays in the system. The long shot helps the user by providing a full spatial model of the information in one view. For example, a flow chart of an hierarchical database showing all the levels and nodes in the database is a long shot. This technique aids the user in establishing a relationship between the display being viewed at any given moment and the entire information structure.

Vicente and Williges (1988) effectively demonstrated the usefulness of world maps for individual differences in the searching strategies used in a hierarchical file system. They incorporated visual momentum by using a partial map of the hierarchical file structure and an analog indicator of the user's position within a file (similar to scroll bars now used in many

applications). Both of these techniques illustrate the use of the long shot which provides a spatial representation of the file structure. They tested for individual differences (groups with low and high spatial abilities) in the searching strategies used with the graphical design to that of a verbal interface. The partial map of the file structure was intended to aid inter-file transitions, and the analog indicator was implemented to aid intra-file transitions. Participants did show a significant improvement with the graphical interface for the average total number of commands used and the average number of different commands used per trial. Searching strategies were shown to be more efficient in the graphical (visual momentum) interface because participants relied less on more inefficient commands like "scroll down" and "zoom out."

Brown, Meehan, and Sarkar (1993) used a "fisheye view" which provides a long shot for browsing large graphs. Traditionally, for users to be able to view sections of large graphs on displays, they had to zoom into the area of interest. In doing so, the global structure of the map was lost because ordinarily there is not enough display space to present the global and zoom-in views. These types of tasks can impose memory demands on users because they are forced to remember how the zoomed-in area of interest fits into the overall global structure of the graph. The fisheye view solves this problem by presenting the area of interest in detail, while the remaining areas in the graph are displayed in progressively less detail as they move farther away from the area of interest. Although the area of interest is shown in detail, a long shot of the entire structure is always visible.

Dorigi, Ellis, and Grunwald (1993) demonstrated that providing an electronic map display, which gave pilots a "birds eye view" (exocentric or outside-in) while performing an egocentric (inside-out) task for target orientation, was a substantial source for improvement in pilot spatial awareness.

The long shot provides a world view that contains summary information, illustrating the relationships between displays and providing a constant system model. Additionally, the long shot highlights salient features of the system that are imperative for developing a mental model of the system.

Perceptual landmarks (anchors), which are highlighted salient features that are consistent between displays, are a very useful technique for integrating information across displays. Perceptual landmarks provide anchors that give users a common frame-of-reference when moving between displays. Because these landmarks are highlighted, they are perceptually easy to locate, quickly orienting the user to the spatial representation of the system.

Aretz (1990) looked at navigation tasks of pilots comparing three different map formats. Two traditional map displays, track-up and north-up, were compared with a map designed to utilize visual momentum that optimized the benefits and costs associated with the two traditional designs. The track-up map provides an ego-centered (egocentric) reference frame (ERF). The orientation of the map always corresponds to the pilot's forward view out of the cockpit. The north-up map establishes a world-centered (exocentric) reference frame (WRF). Regardless of the pilot's forward view

out of the cockpit (heading), the map always has a north-up canonical alignment. With either of the traditional maps, pilots must be able to match their current view of the world (egocentric) with their map display. The degree to which there is cognitive coupling between the pilot's egocentric reference frame and the map display will determine a pilot's navigational awareness. Pilots are often forced to mentally rotate the map reference frame so that it aligns with their egocentric frame-of-reference.

Navigation can impose serious mental workload constraints on a pilot. North-up and track-up both offer advantages and disadvantages in navigation. Track-up aids navigation because left and right turns do not require mental rotation of the ERF map to the egocentric frame-of-reference of the pilot. However, north-up maps have been shown to aid searching for and locating landmarks. Also, pilot communications with other aircraft are facilitated by north-up maps.

One solution to capturing the advantages and minimizing the costs associated with the two types of display maps is to use visual momentum to combine them into one display. Because navigation requires that the pilot integrate information between the ERF and WRF, visual momentum can be used to link the two successive views. Aretz (1990) decided to test this hypothesis by super-imposing the ERF (track-up orientation) over the WRF (north-up orientation). A traditional north-up map was used with a wedge emanating from the aircraft symbol. The wedge provided the "anchor," in this case the ERF, by highlighting the pilots forward FOV.

The results demonstrated that the wedge display design, incorporating visual momentum, facilitated the effective cognitive coupling between the

ERF and the WRF orientations. The data indicates the ERF wedge reduced reaction time for a localization task. The principle of visual momentum allowed the integration of information between the ERF track-up and WRF north-up displays. The wedge display design minimized the costs associated with the north-up design because mental rotation was essentially eliminated, allowing an ERF-based orientation. The wedge design managed to retain all of the advantages of the north-up and track-up designs while minimizing their costs.

You-are-here (YAH) symbols in maps like the ones used in shopping malls can be used as salient landmarks to provide the viewer with an anchor that spatially indicates their location in relation to the overall environment (Levine, 1982). YAHs supply visual momentum by linking two separate terrain features, the map and the viewers position.

The visual momentum techniques described are founded on a spatial framework and capitalize on the human's powerful spatial reasoning skills by supplying a semantic structure from which users can perform their tasks.

Spatial Orientation

Spatial orientation has been associated with the ability to determine one's sense of direction, which has long been considered to be directly linked to cues originating from the environment. Tolman (1948) was one of the first to propose that spatial information is taken in by humans and constructed into a map or simplified model that is composed of key elements (landmarks) from the environment. This map serves as an overview of the spatial relations which exist in space. A cognitive map is like a picture, where all of the information in the map (picture) is available simultaneously

for the person to access (Levine, Jankovic, and Palij, 1982). Kuipers (1983) has suggested a dichotomy for classifying the types of environmental information that are incorporated into a cognitive map: (1) Topological relations provide the relationships between locations or points in space. (2) Metrical relations provide the information about the distance and direction between points. Topological information is capable of developing in people even when incomplete pieces of the environment are experienced because of limited exposure. This information provides the "overview" of spaces and is important for orientation. In addition, metrical relations supplement the overview by providing distance and direction information, helping people to understand where their position in space is in relation to the entire environment. Although, both metrical and topological types of information are important for orientation and navigation in environments (Kuipers, 1983). Furthermore, how the information is acquired can effect the nature of people's cognitive maps (Sholl, 1987). For example, Presson and Hazelrigg (1984) have identified that there can be primary and secondary spatial knowledge. Primary spatial knowledge is acquired directly from the environment, and secondary knowledge is acquired indirectly through other sources, such as maps or models of the environment. Depending on the type of prior learning, the different types of information acquired are represented differently in people and can affect performance in orientation tasks (Sholl, 1987).

Passini (1984) summarized several researchers' notion of spatial orientation as "...a person's cognitive ability to represent space accurately, to map environmental information at the large scale and to determine the

position of the person concerned within that representation." Furthermore, Passini (1992) identified spatial orientation as a "...person's ability to mentally determine his position within a representation of the environment made possible by cognitive maps."

Representations of spaces (cognitive maps), which are closely associated with spatial orientation, have always been thought to underlie navigation behavior (Gordon, Jupp, and Byrne, 1989; Rovine and Weisman, 1989). If an individual has an accurate cognitive map or representation of the surrounding environment, that person should be oriented and more able to navigate through the corresponding space (Evans, 1980). Unfortunately, humans' spatial cognitive maps cannot be observed directly; therefore, they must be inferred from sketch maps, drawings, and other spatially oriented tasks. However, although people have demonstrated the ability to accurately wayfind in an environment, they regularly are unable to accurately provide cartographic spatial descriptions or sketch-maps of the same environment (Passini, 1992). These circumstances allude to the possibility that the sensitivity of the measurement tools currently used may be inadequate. This apparent contradiction, however, may be explained by the fact that wayfinding involves the serial processing of environmental cues along the trip, facilitating storage and retrieval of spatial information. It becomes apparent from this discussion that wayfinding relies heavily on recognition as where the process of communicating one's spatial knowledge relies to a greater extent on the recall of information. Based on the idea that our interest in spatial orientation is directly related to our desire to understand navigation and related performance in real or simulated environments,

Passini (1984) has proposed that the measurement of spatial representations should be assessed according to their utility value and not on cartographic descriptions.

Landmarks in cognitive map building. Experimental studies have repeatedly demonstrated that, in order for spatial orientation to develop in individuals, information from the environment must be comprehended from multiple perspectives. Passini (1992) refers to the "legibility factor" as the quality in which a place lends itself to extraction and comprehension of the spatial information contained within it. In fact, this information varies in quality not only in exterior environment, but in architectural elements as well. For example, O'Neill (1991) claims that "Architectural legibility is the degree to which the designed features of the environment aid people in creating an effective mental image, or 'cognitive map' of the spatial relationships within a building..." Places with a higher legibility factor will facilitate being cognitively mapped into memory. Lynch (1960) determined several key elements that people use to build cognitive maps of places, one of which is landmarks. Explorers have often given accounts of using landmarks to maintain a sense of direction and to perform wayfinding in complex environments. People use landmarks to organize and retrieve other spatial information from an environment (Allen, Siegel, and Rosins, 1978). In addition to landmarks being salient features, Pezdeck and Evens (1979) found that the recall for physical features of a building depended on the features being associated with a function or something as simple as a label. An anchor-point hypothesis of spatial cognition has been put forth which emphasizes the central role salient spatial cues (landmarks) play in the

development of the cognitive structure used by humans for spatial orientation (Couclelis, Golledge, Gale, and Tobler, 1987; Golledge, 1978). Interestingly, it has also been shown that in environments where no significant landmarks exist, people will select items which are not necessarily salient, such as the color of curtains or unique features of doors and use these as landmarks instead (De Jonge, 1962).

In addition to landmarks providing salient cues for spatial orientation, they have also been demonstrated to significantly improve adults' ability to estimate distances (Allen, Kirasic, Siegel, Herman, 1979). Allen, Siegel, and Rosinski (1978) selected scenes based on landmark potential, which refers to the ability of environmental features to serve as spatial reference points. There was a significant improvement for distance estimates for high landmark potential environments. The experimenters concluded that estimates of distance were better because landmarks are an effective way of organizing cognitive representations of spaces. To investigate whether judgment of direction is biased when traversing a winding path, Okabe, Aoki, and Hamamoto (1986) had subjects walk through a winding path and make direction estimates by pointing the needle of a compass to a specified location. As predicted, direction errors were a function of how far the vanishing point of the trail deviated from the required target position; however, when a salient landmark was available, participants were significantly better at making direction judgments.

Spatial orientation in virtual environments. Henry and Furness (1993) compared the spatial ability of architects while touring a museum gallery in either a real museum or in computer-generated galleries. The

computer-generated galleries were viewed under three increasingly immersive conditions: through a perspective display, viewing through a stereoscopic HMD without head-position tracking, and a HMD with head-position tracking. Worth noting is the fact that all three conditions were viewed with a 90° FOV; although, the monitor condition was different from the HMD conditions in that the HMDs isolated the peripheral vision. Participants toured the gallery for 15 minutes while performing spatial dimension and orientation tasks. They were asked to estimate the width, length, and height of each room while in the gallery. Participants also performed several orientation tasks by pointing at an object experienced earlier in the tour but out of sight during the direction judgments.

It was discovered that spatial dimensions were significantly underestimated in all of the computer simulated environments as compared to the real gallery. Surprisingly, the fully immersive virtual environment yielded the poorest distance dimensions, as where the perspective display had the least pronounced underestimates of the three simulated conditions. No differences existed for the orientation task across display conditions. However, the distribution of distance estimates in the simulated conditions were much more dispersed than in the real viewing condition. One explanation for the lack of significant results across display conditions is that the museum gallery was too simplistic a space. Because FOV was not manipulated, it is unclear whether the limited FOV in all the simulated conditions prevented people from forming a cognitive map of the space, and therefore, hindering dimension estimates and orientation judgments.

Arthur, Hancock, and Chrysler (1993) had participants reproduce a spatial layout consisting of nine common objects under virtual and real conditions. Viewing conditions included: binocular real, binocular virtual and monocular real. The latter was viewed from a single viewpoint, and the binocular conditions allowed for active exploration of the space. No significant differences between the binocular real and virtual conditions were demonstrated for a map task that required participants to draw the objects they had viewed on a scaled down representation. The findings of this study suggest that people perceive and develop spatial cognitive maps of objects equally as effective in real and virtual environments.

Integration of Issues

Perception, and therefore the cognitive representation of the visual world, depends on the size of the FOV, and without adequate FOVs, people's ability to acquire spatial information is impeded. Restricted FOVs result in the loss of the total amount of peripheral information normally acquired at any given instance. As a result of this, it has been repeatedly shown that the overlap of information across successive FOVs is reduced. These two consequences have profound effects on the human's ability to develop a spatial cognitive map of unfamiliar spaces, resulting in the orientation of objects in these spaces also being misjudged. Not surprisingly, distortions in the perception of size and distance are also associated with restricted FOVs. And this distortion is manifested as a compressed depth misperception resulting from a telephoto effect.

The negative effects of truncated FOVs in VEs have been shown to be even further inflated. The time taken to acquire, memorize, and recall

targets has been suggested to be an indicator of spatial awareness in VEs. Several additional consequences of restricted FOV have been flushed out in VE research, such as greater memory and attentional demands on the human operator. The magnitude of these human information processing decrements are dependent on task difficulty and type. The sum of these effects from restricted FOVs affects not only the perception and representation of spatial information, but ultimately the performance of humans in VEs. Essentially, people perceive perspective displays with restricted FOVs as the entire VE, rather than a window into the VE.

Visual momentum techniques facilitate the degree to which users can extract and integrate information across displays. This is precisely the solution users need to help them overcome the perceptual and performance problems associated with restricted FOVs. Restricted FOVs, in essence, result in discrete snapshots of successive visual glances with reduced integration and overlapping of information. Visual momentum techniques can assist the analog perception of spatial environments by facilitating the development of spatial cognitive models, compensating for poor model formulation because of restricted FOVs. Visual momentum has also been shown to alleviate excessive memory demands and bottlenecks in attentional resources under similar conditions (across display processing) to those imposed by restricted FOVs. The keyhole and getting lost phenomenon caused by low visual momentum are also precisely the same effect caused by restricted FOVs.

The visual momentum concepts of display overlap, spatial representation, and spatial cognition are inherent in VEs, but the use of the

long shot and perceptual landmarks need to be designed into VEs, which are capable, in addition to the other techniques, of intrinsically overcoming the types of problems caused by restricted FOVs. The long shot affords an overview map of the VE, supplementing the deficiency in the sub-optimal development of the user's spatial cognitive map caused by truncated FOVs. It is hypothesized that the overview map can replace the incomplete spatial cognitive map and thereby return performance to expected levels when an adequate spatial representation has been formed.

In real environments landmarks have been shown to be one of the key features which are used to develop a cognitive spatial map. In doing so, landmarks are then used to organize and retrieve other spatial information from the environment. This property of landmarks was demonstrated in VEs when slower head movements under restricted FOVs suggested that users were matching terrain features with targets to remember them. Experimental studies have repeatedly shown that the environment must be experienced from multiple perspectives. VEs inherently provide information from multiple perspectives, and by including the long shot and salient landmarks, additional perspectives are furnished in the interface.

Salient perceptual landmarks provide anchors that are used as reference points to aid display transversals. When used in conjunction with the long shot, the long shot highlights these anchors, allowing a framework of the spatial environment to materialize. Because of the reduced successive information overlap in restricted FOVs, anchors can alleviate memory demands by serving as mnemonics that can be remembered across discrete-like FOV glances and, therefore, linking the incomplete or limited

successive FOVs. Landmarks have also been shown to improve judgments in direction making. Furthermore, landmarks have been shown to significantly improve people's ability to estimate distances. Direction, size, and distance judgments are the very abilities that are impaired as a result of restricted FOVs. The long shot and salient anchors provide the exocentric world view, in turn, benefiting egocentric tasks, for example, spatial orientation.

One gets the impression from the literature review that there are some gaps in our understanding of how VEs are perceived, which is compounded by ambiguity in the findings that have been collected. However, a few consistent patterns have emerged from the research: (1) Restricted FOVs have a greater impact in VEs than in the real-world. In other words, it takes less restriction in the FOV to produce performance losses in VEs than would occur under larger FOVs in the real-world. (2) The effects of FOV are task dependent. Not only do they depend on the type of task, but they also depend on the complexity or resource demands imposed by the task. (3) Restricted FOV, in and of itself, causes perceptual, cognitive, and performance problems for humans. (4) The perspective parameters used to manipulate GFOV in perspective displays impose additional difficulties by distorting the image producing a telephoto effect. (5) In addition, observers exhibit a misinterpretation of the viewing parameters because their eyes are often not located at the center of projection or the correct distance from the display.

Purpose

VE technologies offer tremendous possibilities for the future. Designers of architecture are among the first who are finding immediate use for VEs. The 3D representation of spatial information makes VEs the perfect tool for simulating architectural spaces. However, before we can use VEs effectively and reliably, a more complete understanding of the human's perceptual, cognitive, and physical capabilities must be understood. Very little research has addressed these fundamental, intrinsic human characteristics in VEs. More specifically, little empirical inquiry has examined whether the basic characteristics of spaces are perceived similarly in real and virtual environments.

The purpose of this research is to determine whether the basic characteristics of architectural space are accurately perceived in VEs and to find the extent to which manipulating the GFOV in perspective displays will affect that perception. In addition, how do VE enhancements based on visual momentum techniques compensate for the perceived biases that are known to exist in perspective displays.

Furthermore, this research is intended to answer the question of whether egocentric judgments of orientation and distance from within the VE, which are based on an egocentric VE frame-of-reference, corroborate perceptual biases found under a variety of other conditions in perspective displays. Moreover, the degree of GFOV restriction and how it interacts with task difficulty will be examined. Restricted FOVs prevent the adequate development of cognitive maps for spaces resulting in reduced spatial

orientation, and perceptual biases result because of misinterpreting the viewing parameters used to generate perspective displays.

Therefore, it is the aim of this study to confirm the hypothesis that visual momentum techniques, which symbolically enhance the VE, will significantly remove perceptual, cognitive, and performance problems associated with restricted GFOVs in perspective displays. Specifically, the research discussed earlier in this thesis suggests several hypothesized outcomes for this study.

1. The telephoto effect caused by restricted GFOV will produce perceptual and performance errors for egocentric judgments of size and distance.
2. Restricted FOV in the perspective display will cause distance underestimation and will reduce the ability of participants to maintain spatial orientation and representation.
3. Increases in task difficulty will be more detrimental to distance estimates and spatial orientation and representation as the FOV is further restricted.
3. Providing visual momentum in the interface will help eliminate perceptual and performance errors caused by the telephoto effect as the result of restricted GFOV.
4. Visual momentum will significantly improve the ability of participants to maintain spatial orientation and representation under restricted FOVs but will be less beneficial as the FOV widens.
5. Participants with higher spatial abilities will be able to better maintain spatial orientation and representation under restricted FOVs.

6. Participants in the visual momentum conditions will rate their performance more favorably.

METHOD

Experimental Design

A 3 x 2 x 2 mixed, factorial design was used with three levels of GFOV (30 x 27, 60 x 50, and 90 x 80) (degrees azimuth x degrees elevation), two levels of Visual Momentum (Low and High), and two levels of Difficulty (Easy and Hard). Geometric Field-of-view and Visual Momentum are the between-subjects factors and Difficulty is the within-subjects factor. The experimental design has 6 conditions with 10 subjects per cell for a total of 60 subjects (see Figure 6). Dependent variables which do not include the within-subjects factor (Difficulty) were analyzed with the 3 x 2 between-subjects factors portion of the design.

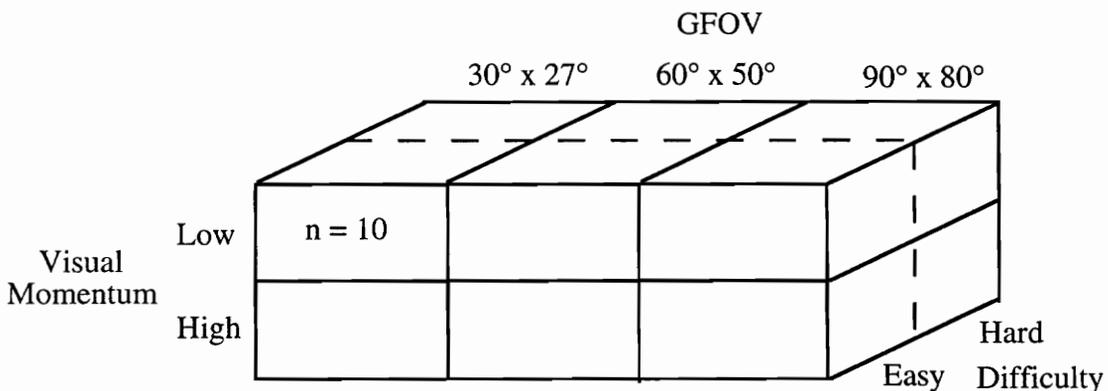


Figure 6. 3 x 2 x 2 mixed, factorial design.

To control for order effects in the within-subjects factor, the order in which the pointing tasks (Easy vs. Hard Difficulty) were performed was counter balanced across subjects and tasks. Furthermore, the order of the tasks was randomized for each subject. In other words, half the subjects received the Easy Difficulty pointing condition first and half received the

Hard Difficulty pointing condition first. In addition, across the tasks half the subjects received the Easy Difficult condition first, and the other half received the Hard Difficulty condition first. Table 1 shows the treatment order for all 60 subjects. A number 1 in the matrix corresponds to the

Table 1. Treatment order for the within-subjects factor.

Subject	rmB	rmC	rmD	rmE	rmF	rmG	Subject	rmB	rmC	rmD	rmE	rmF	rmG
1	1	1	2	1	2	2	31	1	2	1	2	1	2
2	1	1	2	2	2	1	32	1	1	2	1	2	2
3	1	1	2	2	1	2	33	1	2	2	2	1	1
4	1	2	2	1	2	1	34	1	1	2	1	2	2
5	1	2	1	2	1	2	35	1	1	2	1	2	2
6	2	2	1	2	1	1	36	2	1	2	1	1	2
7	2	1	2	1	1	2	37	2	2	1	2	1	1
8	2	1	2	1	2	1	38	2	2	1	1	1	2
9	2	1	2	1	1	2	39	2	1	2	2	1	1
10	2	1	2	1	2	1	40	2	2	1	1	1	2
11	1	2	1	2	2	1	41	1	2	1	2	2	1
12	1	2	2	1	1	2	42	1	2	2	1	1	2
13	1	1	1	2	2	2	43	1	1	2	1	2	2
14	1	1	1	2	2	2	44	1	2	1	1	2	2
15	1	1	2	1	2	2	45	1	2	2	1	2	1
16	2	2	1	2	1	1	46	2	2	1	1	1	2
17	2	1	1	1	2	2	47	2	1	2	1	2	1
18	2	1	2	2	1	1	48	2	1	1	1	2	2
19	2	2	1	2	1	1	49	2	1	1	2	2	1
20	2	2	2	1	1	1	50	2	2	1	2	1	1
21	1	1	2	1	2	2	51	1	1	2	1	2	2
22	1	1	2	2	1	2	52	1	1	2	2	2	1
23	1	2	1	1	2	2	53	1	2	1	1	2	2
24	1	2	2	2	1	1	54	1	1	2	2	2	1
25	1	1	2	2	2	1	55	1	2	1	2	2	1
26	2	2	1	1	1	2	56	2	2	1	2	1	1
27	2	2	1	1	2	1	57	2	2	1	1	1	2
28	2	1	2	1	1	2	58	2	1	1	1	2	2
29	2	1	1	2	2	1	59	2	2	1	1	1	2
30	2	1	2	2	1	1	60	2	2	2	1	1	1

subject receiving the Easy Difficulty condition first, and a number 2 corresponds to the subject receiving the Hard Difficulty condition first.

The three GFOVs were chosen for this experiment based on previous findings in the real-world and in VEs. First, they represent adequate choices for reproducing the range of restricted FOV effects found in VEs and the real-world. Secondly, 30° (telephoto), 60° (normal), and 90° (wide angle) represent the full spectrum of effects in the GFOVs produced by synthetic cameras in perspective displays. In other words, the telephoto and wide angle effects known to cause perceptual biases are created by 30° and 90°. The GFOVs referred to here are the horizontal visual fields. The width of the visual field is almost more than double that of elevation and more central to the issues of perception in general. Much of the literature concerning this topic only provides the horizontal FOV or GFOV metric. Therefore, the horizontal GFOV that is desired for experimentation is set, and the corresponding GFOV for elevation is provided automatically by the software. In most cases, this is an appropriate setting considering the horizontal visual angle chosen.

In the High Visual Momentum conditions, the VE included a long shot and salient landmarks. The Low Visual Momentum conditions did not include these techniques but have spatial representation. The Easy and Hard Difficulty level for the within-subjects factor corresponds to the degree of difficulty required for spatial orientation. Orientation difficulty was partitioned into Easy and Hard to create a greater range in the effect for this factor because of the lack in sensitivity which has been shown to exist for point-to-unseen-targets in VEs (Henry and Furness, 1993). Also,

performance decrements as a result of restricted FOVs have been shown to be task dependent.

Dependent Variables

The dependent variables include: (1) estimates given in feet of the width and length in each of the rooms experienced by the subjects (square footage). (2) Pointing-to-unseen-targets, Easy and Hard Difficulty conditions, was measured using absolute angle displacement in degrees azimuth from the position of the center of the reticle to the orientation task object during direction judgments. (3) Along with the pointing tasks, subjects gave estimates in feet for the distance from their pointing position to the orientation task object. Following the initial tour of the space, subjects were asked to draw a sketch map of the test environment. (4) Several measures are analyzed and combined into a composite score for sketch map accuracy: the number of rooms and their correct placement, number of doors and their correct placement, number of hallways correctly placed, and room proportions.

In the 2nd phase of the experiment, subjects reconstructed the furniture layout of a virtual room which they had previously examined. The (5) time taken to reconstruct the room layout, and (6) the accuracy for the number of items correctly placed within 2 feet of their original position were the measures collected for the reconstruction task. Lastly, (7) a subjective questionnaire was administered following the experimental session to collect participants' opinions regarding their experience in the VE (see Appendix A).

Subjects

The participants were individuals recruited from the Virginia Tech campus. They all were required to have at least 20/40 corrected vision and be able to discriminate colors. In addition, they were required to have some familiarity with computers and the use of a mouse as an input device. A total of 60 individuals participated in this study.

Participants were not selected or divided into groups experimentally on the basis of spatial ability. The predominant reason for not experimentally blocking for spatial ability is because, in a very practical sense, no assumptions can be made about the spatial ability of individuals using these types of applications, who may or may not have the developed spatial abilities found in architects, engineers, visual artists, et cetera. Craik (1976) points out that, although specific subgroups sometimes warrant investigation, such as those thought to possess special competence in spatial ability, the best subjects for environmental research are often those who are a representative sample of the general public. Furthermore, in a study to determine the relationship between spatial ability and environmental knowledge, Pearson and Ialongo (1986) compared the scores of college undergraduates on four standardized measures of spatial ability and two measures of environmental knowledge. A significant correlation did not exist between spatial ability and environmental knowledge. Based on these findings, the experimenters reported that regardless of the purported dimensions in either environmental knowledge or spatial ability, in all probability, there will not be a significant relationship between the two constructs (Pearson and Ialongo., 1986). The tasks in this study rely on

environmental knowledge, and although these findings suggest that spatial ability may not be a factor for environmental knowledge, the ability to maintain orientation with respect to objects in space is likely to be affected by spatial ability. Therefore, spatial ability was not used as a blocking factor, insuring that people with a full range of spatial ability participated in the experiment. Instead, subjects were tested for spatial ability prior to participating in the experiment for consideration in post-hoc analyzes.

Materials and Apparatus

Vision tests. The Bausch & Lomb[®] Vision Tester was used to measure visual performance. The Vision Tester is a standard instrument for measuring visual abilities. Acuity was measured by administering Test F-3 (acuity both eyes near). Color vision proficiency was determined by section one of the Dvorine Pseudo-Isochromatic Plates test (Dvorine, 1953). The test consists of 14 plates with color combinations arranged in pairs.

Spatial abilities test. The Factor-Referenced Cognitive Test Kit (Ekstrom, French, and Harmon, 1976) using the spatial orientation Cube Comparisons Test (form S-2) was used to determine the participant's ability to maintain orientation with respect to objects in space. This spatial test was selected based on previous findings by Antin, Dingus, Hulse, and Wierwille (1988). These researchers found that spatial ability predicted by this test significantly affected navigation performance while traversing routes in an automobile using various map displays. In addition, the Cube Comparisons test was significantly correlated with two other spatial abilities tests from the Factor-Referenced Cognitive Tests Kit (Identical Pictures and Map Planning). Navigation performance and the tasks in this study are

considered to be affected by the ability of a person to remain oriented in relation to objects in space.

Computer. A Macintosh® Quadra 840AV was used as the apparatus for presenting stimuli to participants because of its ability to display real-time graphics demanded by VE applications. It was used in conjunction with an extended keyboard, mouse, 14" AV monitor, and a 21" color display.

Virtual environment application Virtus® WalkThrough Pro™ is a 3D, VE computer-aided drawing and visualization tool for spatial design. Two categories of VE software are toolkits and authoring packages. Toolkits contain programming libraries and generally require a skilled programmer to create VE applications. Authoring packages usually have GUIs and do not require the detailed programming as with toolkits; however, they often do have higher level scripting languages which can be used to describe complex actions. Walkthrough Pro™ is an authoring VE application designed for use with perspective displays which provides 3D modeling. It allows the user to walk through VEs in real-time, but dynamic interaction with objects is not supported. Polygons are drawn in a 2D "Design View" and then inflated and rendered into 3D objects and environments in the "Walk View." The Walk View, or 3D modeling view, allows the user to navigate through environments that were created in the Design View. The application also supports texture mapping and QuickTime movies. Walkthrough Pro™ falls into the category of desktop VR previously discussed.

The walk through in the VE is from an egocentric viewpoint. Navigation through the VE is in response to the mouse position relative to the cross hairs that are centered in the Walk View window. If the mouse pointer is above the cross hair, forward movement results, and when it is below the cross hairs, the observer's viewpoint moves backward. When the mouse pointer is to the left or right of the cross hairs, movement occurs in the corresponding direction. However, the mouse button must be depressed for any movement to occur. The velocity of movement increases as the cursor moves away from the cross hairs. When the mouse is used in conjunction with the option key, the user's viewpoint slides left or right rather than turning.

Virtual environment. Craik (1976) has summarized several presentation methods for environmental information: (1) direct experience, (2) cinematic and photographic methods, (3) sketches, drawings, and models, and (4) simulative exploration. There are advantages and limitations to each of the approaches listed above. In the past, dynamic environmental simulation has taken on several forms: (1) dynamic conceptual computer simulation techniques which model the human by sets of rules or other predictive methods (Gopal, Klatzky, and Smith, 1989; Smith, Pellegrino, and Golledge, 1982), and (2) dynamic perceptual approach using sequences of images from photographs or videotapes (Cornell and Hay, 1984; and Pearson and Ialongo, 1986; Weisman et al., 1987). Recently with the developments in computer technology, 3D perspective images are dynamically presented, allowing the observer to freely explore and interact with the environment (Henry and Furness, 1993;

O'Neill, 1992). Simulated VEs allow for the control of extraneous variables which can confound results obtained in the real-world. In addition, many environmental variables can easily be manipulated and simulated in VEs.

The environmental stimulus consisted of a simulated office building with 8 rooms connected by several hallways. See Figure 7 for the floor plan layout of the test environment with room dimensions given in feet. Several

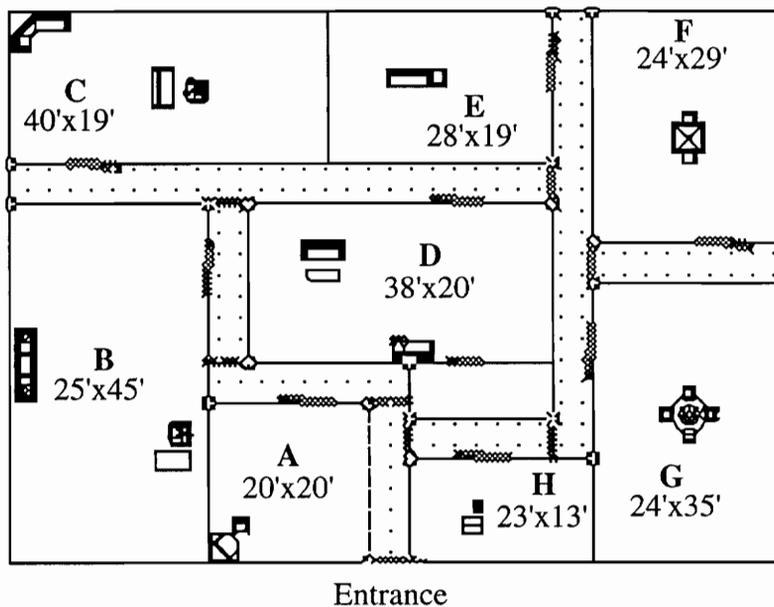


Figure 7. Floor plan for the simulated office building.

pieces of office furniture have been carefully placed in each of the rooms to provide scale dimensions for the environment. The VE was intentionally designed to be complex but no more so than what could be found in an average office building.

Several researchers have demonstrated that familiarity with the environment affects the accuracy of the cognitive map (Evans, Marrero, and Butler, 1981; Mainardi Peron, Baroni, Job, and Salmaso, 1990; O'Neill,

1992); therefore, to eliminate the uncontrolled differences in the cognitive representations of participants, a totally unfamiliar environment was used. Because the update rate for the real-time presentation of perspective images is adversely effected by the number of polygons in the model (detail), the setting was kept relatively simple by using only interior spaces with no windows and diffuse lighting. See Figure 8 for an example of the VE.

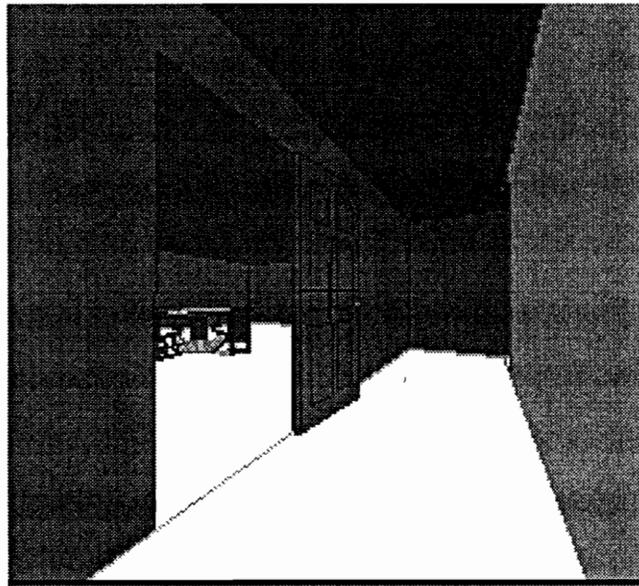


Figure 8. Sample view outside room G in the VE.

Also, the entire VE is portrayed only in shades of gray. However, for the Visual Momentum conditions, landmarks are made salient by displaying them in color. For example, the construction cone is orange. Figure 9 shows the floor plan layout with the placement of landmarks in the environment. Each room had one colored landmark placed in it. In addition, because decisions must be made at choice points (hallway intersections), these areas become highly salient nodes (landmarks) in cognitive maps

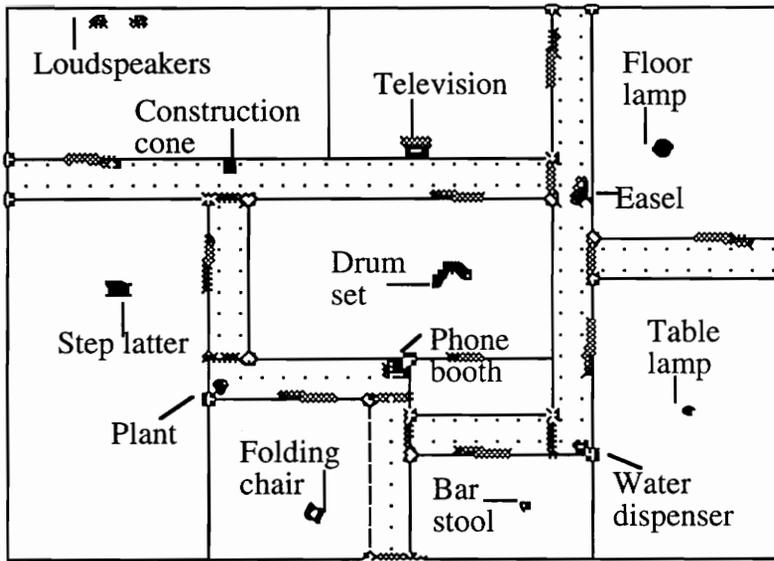


Figure 9. Floor plan for the simulated office building with landmarks only.

(Lynch, 1960; O'Neill, 1991); therefore, salient colored objects (landmarks) were placed at major hallway intersections in the VE.

The floor plan with furniture for the VE room that was used in the reconstruction task is shown in Figure 10. The room is 20 feet by 15 feet

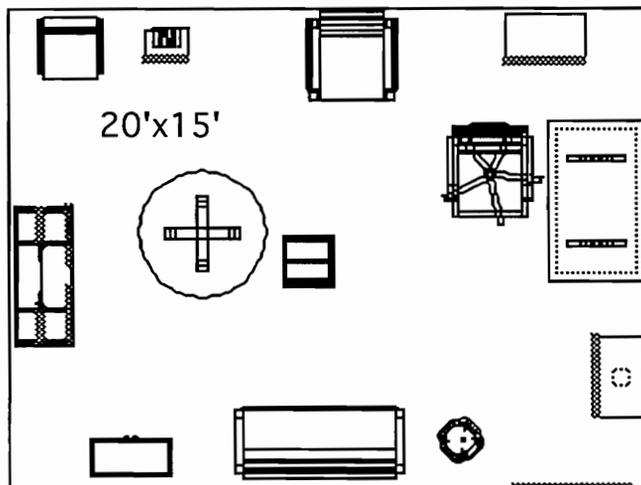


Figure 10. Floor plan of VE room for reconstruction task.

and contains the following 13 objects: desk, office arm chair, book case, round table, loudspeaker, chair, couch, lounge chair, floor lamp, executive chair, file cabinet, table, and cabinet. For the Visual Momentum conditions, four landmarks were added to the room: blue bar stool, light brown end table, dark brown coffee table, and a green plant. Figure 11 shows an overview of the room without landmarks.

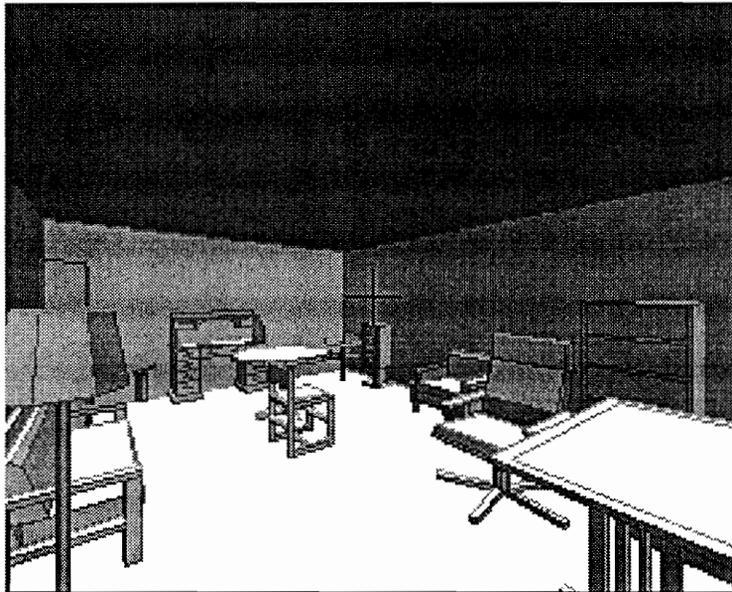


Figure 11. VE room for reconstruction task.

Procedure

Prescreening and training. Each subject was brought into the experimenter area, briefed on the nature of the research, provided with an introduction to the study (see Appendix B), and asked to fill out an informed consent form (see Appendix C). They were then given the Bausch & Lomb® vision acuity test (F-3) to insure that they had at least 20/40 corrected vision. Color vision was then measured using the Dvorine Pseudo-Isochromatic Plates test . If they met the vision requirements, participants were administered the Cube Comparisons Test (form S-2) from the Kit of Factor-Referenced Cognitive Tests.

After completing pre-testing, participants viewed a pre-recorded instructions video demonstrating the computer application. Participants performed several navigation tasks in a practice VE. Following practice, participants were given a set of general instructions to read for phase I of the experiment (see Appendix D).

All participants were presented with the Walk View which allowed navigation throughout the VE. Only subjects in the Visual Momentum conditions had the overview map (long shot) with salient (colored) landmarks. Also, prior to starting they were told to remember the location of the entrance because they would be required to point to it throughout the tour. Subjects started at the entrance of the VE and followed a predetermined path. However, they were allowed to freely explore each space in the VE as they encountered it. Participants were instructed by the experimenter via a two-way intercom while navigating and performing tasks in the VE. See Appendix E for a transcript of the verbal instructions.

Participants were instructed to try and understand and remember the layout of the space as they moved through the virtual building.

Room dimension estimates. Subjects were guided to space A and asked to estimate the dimensions (width and length) of the room.

Participants were specifically instructed not to use furniture or any other method to try and measure or count off the dimensions of the space. They were asked to simply estimate the dimensions from their general impression of the room size. Vertical height of the rooms was not estimated because participants are very accurate at estimating aspects of interior spaces that usually come in standard dimensions, and also because the standing posture helps people use their vertical height as a scale (Henry and Furness, 1993). Room distance estimates as a dependent variable are intended to assess how accurately people perceive the most basic dimensions of virtual space and to what extent manipulating GFOV has on that perception. While they were in space A, they were given instructions to pay particular attention to the chair in the corner because they would be required to determine its location from the next room.

Direction judgments. Participants were directed to the center of each successive room in the VE and asked to point to either the entrance (Hard Difficulty) or the object (Easy difficulty) they were instructed to pay attention to in the previous room (the order of tasks were balanced across all subjects). Pointing tasks were performed in 6 out of the 8 rooms (B through G) with the first and last rooms being excluded. There are a total of 12 judgments to be performed by each participant, 6 in the Easy Difficulty conditions and 6 in the Hard Difficulty conditions. The experimenter took a

snapshot of the screen during each orientation task which was then used to calculate the angle in degrees azimuth from the center of the reticle (cross hairs) to the orientation object location. Pointing in the direction of an unseen reference object is a commonly used method for examining the degree of orientation observers have in real environments (Gordon et al., 1989; Lindberg and Garling, 1981; Sholl, 1987; Okabe et al., 1986) and in VEs (Henry and Furness, 1993; Wells and Venturino, 1990).

Distance estimates. After each pointing task, participants were asked to estimate the distance to the object for which they made the direction judgment. Distance estimates have also been a common task for determining the level of spatial familiarity with an environment (Gordon et al., 1989; Kosslyn, Pick, and Fariello, 1974; Lindberg and Garling, 1981). Following the pointing tasks and distance estimates to the orientation task object in each of the rooms, subjects were asked to estimate the dimensions of the space.

Cognitive map task. After completing the tour of the virtual office building, participants were given an 8 1/2 by 11 blank sheet of paper and asked to draw the floor plan of the VE they just experienced. Sketch maps have been one of the most common methods used for the extraction of environmental cognitive information (Evans, 1980; Lynch, 1960; O'Neill, 1991; O'Neill, 1992; Rovine and Weisman, 1989). Furthermore, Blades (1990) demonstrated that sketch maps are a reliable source of data based on a test-retest methodology where subjects were required to produce a sketch map of the same environment on two separate trials.

Room reconstruct task. Phase II of the experiment involved reconstructing the layout of a VE room. Participants viewed an instruction video demonstrating how to move objects in the 2D Design View. Following the video, participants were allowed to practice moving and rotating furniture in a practice VE. After reading the general instructions for Phase II (see Appendix D), participants were allowed to view and move freely throughout the room for 1 minute. The Visual Momentum conditions included the long shot (overview map) with landmarks. Landmarks were left in the room during the reconstruction task for the Visual Momentum conditions. Participants were instructed to remember the layout of the furniture while in the room. After exploring the environment, all the furniture was removed and placed outside the room. The Design View and the Walk View were available to all the participants during the reconstruction task. Participants were asked to reconstruct the layout of the room as quickly and as accurately as possible.

Reconstructing an environment with objects that were previously viewed has been shown to be a valid method for investigating the accuracy of subject's cognitive maps (Herman and Siegel, 1978; Alfano and Michel, 1990). Time and errors were collected by the experimenter. Errors were determined by the percent of furniture items not correctly placed within 2 feet of their original position. Alfano and Michel (1990) used relative error for replacing objects (within 1 foot of original position) in a spatial orientation task under restricted FOVs and found it to be a predictive measure of spatial orientation performance. Snap shots of the screen were used to determine placement errors for the objects in the room.

Questionnaire responses. Lastly, participants completed a subjective questionnaire (Appendix A), responding to nine questions which used a seven point Likert-type scale. Questions 1 and 6 through 9 asked participants to rate how well they perceived they performed on the various tasks in the experiment. Questions 2 through 5 were adapted from a lexicon of architectural descriptors developed by Kasmar (1970) and were intended to measure whether the independent variables influenced the psychological impression of the virtual space. The adjective pairs borrowed from the list of descriptors were developed and intended to be used by laymen for describing physical environments. The experiment took approximately 1 1/2 to 2 hours to complete for each participant.

RESULTS

The results and discussion sections will use FOV and GFOV interchangeably. Recall the claim was made that the two constructs are considered to be conceptually and theoretically equivalent for most intensive purposes. Although the technical nature of GFOV and its associated parameters are important for understanding the perceptual errors which result, much of the discussion on spatial representation views GFOV to be equivalent to FOV. In other words, the GFOV for perspective displays is the FOV for desktop VEs and is equivalent to its real-world counterpart.

Several analyses were performed and are grouped into two broad categories: 1) analysis for performance relating to basic space dimension estimates, and 2) evaluation of spatial orientation. Basic space dimension estimates include evaluations of room dimensions and distance estimates to unseen targets previously viewed. Room dimensions were tested by comparing participants responses for the width and length of rooms given in whole feet. Dimensions are combined to provide total square footage for each room. Distance estimates to unseen objects were collected and tested to determine the effect of independent variables on the ability to judge the distance from the participant's virtual egocenter to 1) the entrance of the building (Hard Difficulty) and 2) an object from the previous room (Easy Difficulty).

Spatial orientation was analyzed by results from the cognitive map task, direction judgments (pointing), error for object placement, and time to place objects in reconstructing the furniture layout of a virtual room. Cognitive map accuracy performance for each participant was analyzed by

developing a composite score. Interrater reliability was also determined for map scores. Degrees azimuth provided accuracy results for direction judgments from the participant's virtual egocenter to 1) the entrance of the building (Hard Difficulty) and 2) an object from the previous room (Easy Difficulty). Object placement for the reconstruction task was analyzed by the percent of objects correctly placed within 2 feet of their original position. Then, overall time to reconstruct the furniture layout was analyzed to determine the speed of object placement. In addition, spatial ability was tested for its effect on both space dimension estimates and spatial orientation performance. Also, questionnaire results were compared across the independent variables. Lastly, correlations were calculated between relevant dependent measures and between dependent measures and questionnaire data.

Only the direction judgments and distance estimates to unseen objects were analyzed with the 3 x 2 x 2 mixed-factor experimental design. All other dependent measures were analyzed with the 3 x 2 between-subjects portion of the design. These dependent measures did not include the within-subjects factor of Difficulty.

It was suspected *a priori* that spatial ability could influence the behaviors exhibited in this experiment. Therefore, because spatial ability was not used as a blocking variable, analysis of covariance (ANCOVA) was used *a posteriori* to statistically, rather than experimentally, remove variability in performance caused by differences in spatial ability. The concomitant variable, measures on spatial ability, is defined as the covariate for the analysis. The main criteria for using the covariate in the analysis is it

must have a significant linear relationship with the dependent variable (Keppel, 1991). To test this, two analyses were performed for all of the dependent variables and the covariate. Pearson correlation coefficients (R) between all dependent measures and the covariate were formed and 95% confidence intervals were calculated for the correlations. Confidence intervals produce the same results as t-tests by determining if the correlation is significantly different than zero. If the two variables are not significantly correlated, the value of zero is likely to be included in the confidence interval. Therefore, if zero is not included in the confidence interval, the two variables are statistically significantly correlated. Table 1 in Appendix F lists all the correlations and corresponding confidence intervals between the covariate and dependent measures.

Least Significant Difference (LSD) tests were performed on all pairwise comparisons between groups for variables with a significant F-ratio. Although the LSD test is the least stringent in the category of post-hoc tests, family-wise error is controlled by greatly restricting the number of comparisons to conditions when the overall null hypothesis is false. In addition, because individual variability in spatial ability is removed statistically, rather than experimentally, it would be expected that less of a difference between group means would result because a greater proportion of participants with "average" spatial ability are included in the analyses—a normal distribution was found for spatial ability across participants in this study. Conversely, when experimentally blocking for spatial ability, one would adopt an approach of including only those individuals with either low or high spatial ability, and therefore, more precisely isolating the effects of

spatial ability. Because of these conditions, a less conservative post-hoc test was chosen.

Analysis on Space Dimension Judgments

The results for room dimension estimates are intended to reflect the impact of Visual Momentum (VM) and FOV on how people perceive the basic characteristics of virtual spaces. Distance judgments to unseen targets are intended to reflect these same perceptions in addition to providing a measure of spatial orientation—if targets are viewed, and then movement is required through the space before distance judgments are required to the unseen target, spatial orientation is going to influence that judgment.

Analyses of room dimension estimates. A two-factor analysis of variance (ANOVA) was performed on the average square footage estimated from all 8 rooms in the VE. Table 2 provides the ANOVA summary table.

Table 2. ANOVA Summary table for room size estimates.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	363948.817	363948.817	1.061	0.3076
FOV	2	1277851.900	638925.950	1.862	0.1652
VM * FOV	2	1400375.033	700187.517	2.041	0.1398
Residual	54	18527979.100	343110.724		

Dependent: Room Sizes

No significant differences were found to exist between groups for this analysis. Although there were large differences between group means, the standard deviation statistic indicated that the within-group variance was high. See Table 2 in Appendix F for a summary of room size means and standard deviations.

There is a significant correlation ($R = - 0.372$) between the covariate (spatial ability) and room size estimates. Therefore, a two-factor ANCOVA was performed on room size estimates and is presented in Table 3. The ANCOVA table shows the main effects, interactions, and the regressor

Table 3. ANCOVA Summary table for room size estimates.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	1390870.830	1390870.830	5.502	0.0232
FOV	2	2340308.657	1170154.328	4.629	0.0145
Spatial	1	2693876.619	2693876.619	10.657	0.0020
VM * FOV	2	1537266.782	768633.391	3.041	0.0571
VM * Spatial	1	1175516.774	1175516.774	4.650	0.0361
FOV * Spatial	2	1719467.255	859733.628	3.401	0.0416
VM * FOV * Spa...	2	952915.654	476457.827	1.885	0.1629
Residual	48	12133373.974	252778.624		

Dependent: Room Sizes

variable for the independent variables. When considering the results presented in the following analyses on room size estimates, it may be helpful to reflect on that the actual overall average room size is 676.5 square feet.

A main effect for VM was found for room size estimates $F(1, 48) = 5.502, p = 0.0232$. The VM main effect is shown in Figure 12. The High VM groups estimated room sizes to be significantly larger than the Low VM groups. A FOV main effect was also found to be significant $F(2, 48) = 4.629, p = 0.0145$. Figure 13 shows the main effect for FOV. Table 3 in Appendix F shows the LSD test for pairwise comparisons among the three FOV groups. The 30° FOV group estimated the rooms to be significantly smaller than both the 60° and 90° FOV groups. In addition to the analyses

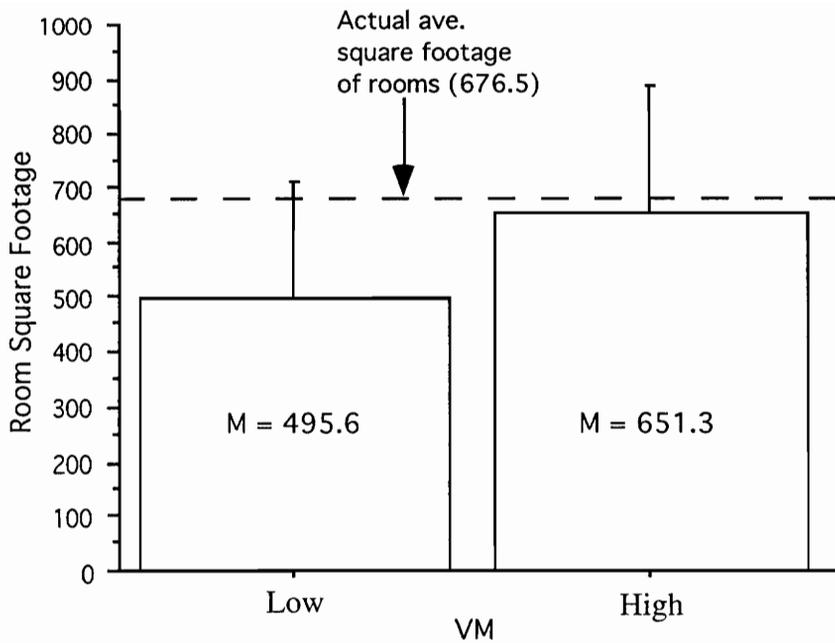


Figure 12. Overall mean room size estimates for VM.

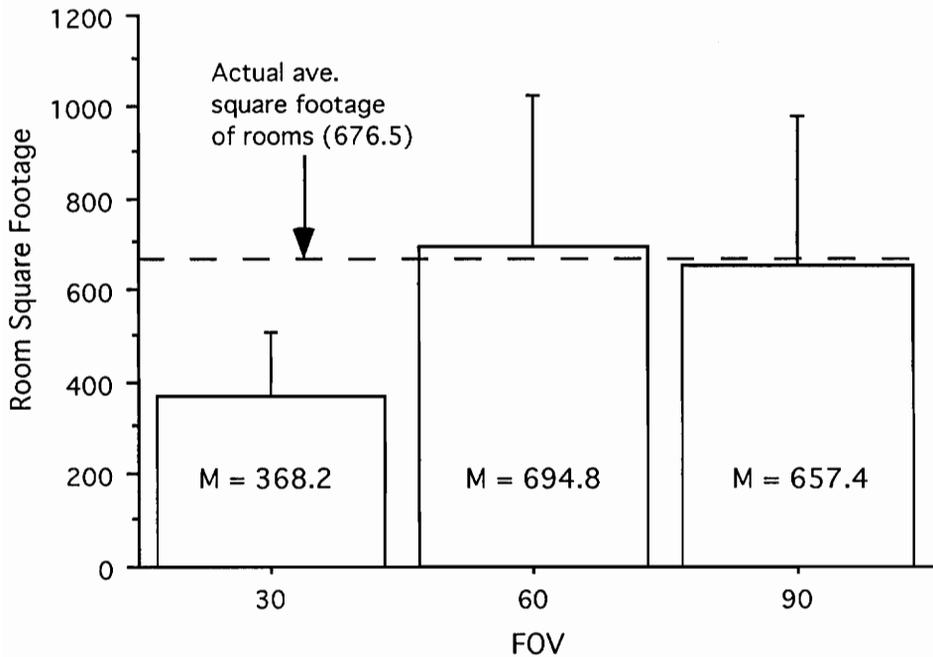


Figure 13. Overall mean room size estimates for FOV.

just presented, rooms were analyzed individually, and no learning effect occurred as participants estimated room sizes for additional rooms.

A significant VM by FOV interaction was found for room size estimates when the variability due to spatial ability was factored out $F(2, 48) = 3.041, p = 0.0571$. Figure 14 shows the relationship between VM and FOV. See Table 3 in Appendix F which contains all LSD pairwise

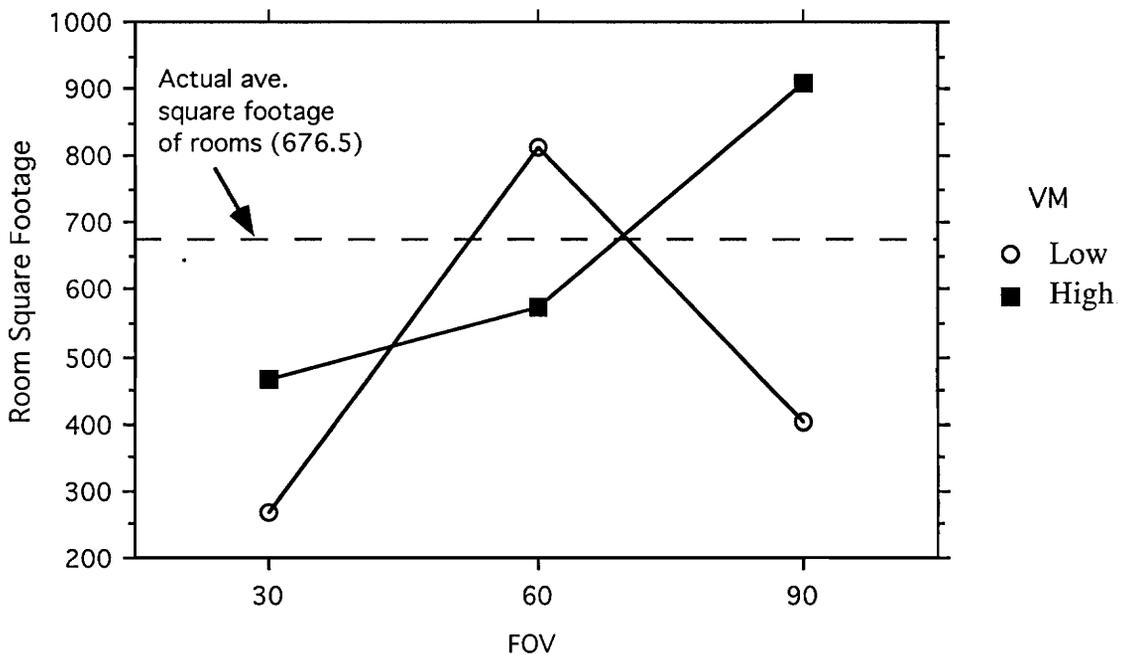


Figure 14. Interaction between VM and FOV for room size.

comparisons for room size estimates. VM had little effect on room size estimates for the 30° FOV and 60° FOV conditions but had significant effect on the 90° FOV conditions. Room size estimates were significantly larger for the 90° FOV condition when there was High VM than when there was Low VM. Also, the High VM, 30° FOV and High VM, 60° FOV groups

estimated room sizes to be significantly smaller than the High VM, 90° FOV group. Lastly, the Low VM, 60° FOV group estimated room sizes to be significantly larger than both the Low VM, 30° FOV and Low VM, 90° FOV groups.

Analysis of distance estimates. Distance judgments were analyzed with a three-factor, mixed-subjects design. The within-factor, Difficulty, contains the two types of distance judgments. Judgments in the Easy Difficulty conditions were to objects from the previous room visited, and judgments in the Hard Difficulty conditions were always to the entrance of the building. For purposes of comparison while examining the results for distance estimates, the actual overall mean distance to objects was 35 feet and the mean distance to the entrance was 51 feet. Table 4 shows the ANOVA summary table.

Table 4. ANOVA summary table for distance estimates.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G	H-F
VM	1	212773.408	212773.408	1.444	0.2347		
FOV	2	759106.617	379553.308	2.577	0.0853		
VM * FOV	2	231769.717	115884.858	0.787	0.4605		
Subject(Group)	54	7954225.350	147300.469				
Difficulty	1	1331202.675	1331202.675	33.401	0.0001	0.0001	0.0001
Difficulty * VM	1	453747.008	453747.008	11.385	0.0014	0.0014	0.0014
Difficulty * FOV	2	183564.050	91782.025	2.303	0.1097	0.1097	0.1097
Difficulty * VM * FOV	2	109260.817	54630.408	1.371	0.2626	0.2626	0.2626
Difficulty * Subject(Group)	54	2152198.950	39855.536				

Dependent: Distance

Epsilon Factors for df Adjustment

G-G Epsi... H-F Epsilon

Difficulty	1.000	1.094
------------	-------	-------

A significant main effect was found for the Difficulty factor $F(1, 54) = 33.401, p = 0.0001$ and for the Difficulty by VM interaction $F(1, 54) = 11.385, p = 0.0014$. However, because there was a significant correlation between the covariate and the distance judgments to objects ($R = -0.312$) and distance judgments to the entrance ($R = -0.264$), the full analysis will only be reported for the ANCOVA performed on distance judgments. Table 5 includes the ANCOVA summary table for distance estimates. Additional

Table 5. ANCOVA summary table for distance estimates.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G	H-F
VM	1	11891.822	11891.822	0.103	0.7493		
FOV	2	1574309.379	787154.690	6.839	0.0024		
Spatial	1	985138.221	985138.221	8.559	0.0052		
VM * FOV	2	477132.064	238566.032	2.073	0.1370		
VM * Spatial	1	93591.511	93591.511	0.813	0.3717		
FOV * Spatial	2	1100777.503	550388.751	4.782	0.0128		
VM * FOV * Spatial	2	371758.716	185879.358	1.615	0.2095		
Subject(Group)	48	5524810.611	115100.221				
Difficulty	1	665562.427	665562.427	18.155	0.0001	0.0001	0.0001
Difficulty * VM	1	161772.016	161772.016	4.413	0.0409	0.0409	0.0409
Difficulty * FOV	2	328891.060	164445.530	4.486	0.0164	0.0164	0.0164
Difficulty * Spatial	1	197485.705	197485.705	5.387	0.0246	0.0246	0.0246
Difficulty * VM * FOV	2	96061.451	48030.725	1.310	0.2792	0.2792	0.2792
Difficulty * VM * Spatial	1	30221.049	30221.049	0.824	0.3684	0.3684	0.3684
Difficulty * FOV * Spatial	2	215420.912	107710.456	2.938	0.0626	0.0626	0.0626
Difficulty * VM * FOV * S...	2	42259.036	21129.518	0.576	0.5658	0.5658	0.5658
Difficulty * Subject(Group)	48	1759640.577	36659.179				

Dependent: Distance

Epsilon Factors for df Adjustment

G-G Epsi... H-F Epsilon

Difficulty	1.000	1.234
------------	-------	-------

measures were found to be significant with the ANCOVA. Main effects were found to exist for the FOV and Difficulty factors. Figure 15 shows the main effect for FOV $F(2, 48) = 6.839, p = 0.0024$. The LSD test

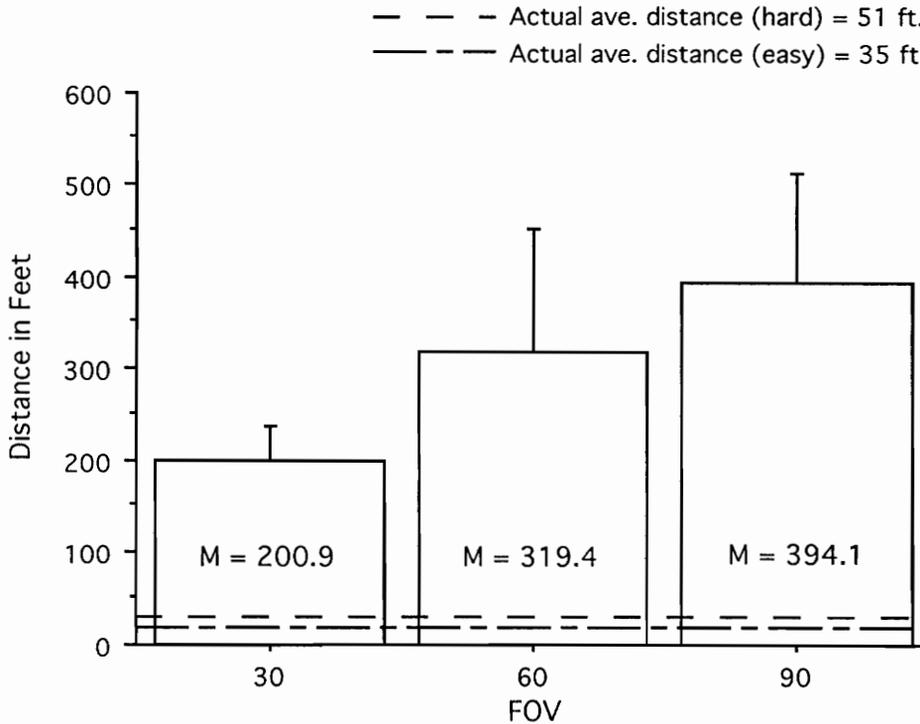


Figure 15. Mean distance estimates for FOV.

results for FOV are in Table 4 of Appendix F, and Table 5 in Appendix F lists the summary of group means and standard deviations for all the distance estimates. The 30° FOV conditions estimated distances to be significantly shorter than both the 60° FOV and 90° FOV groups. The main effect for Difficulty is shown in Figure 16 $F(1, 48) = 18.155, p = 0.0001$. Distances were judged to be significantly shorter in the Easy Difficulty conditions than in the Hard Difficulty conditions. However, as can be seen in Figures 15

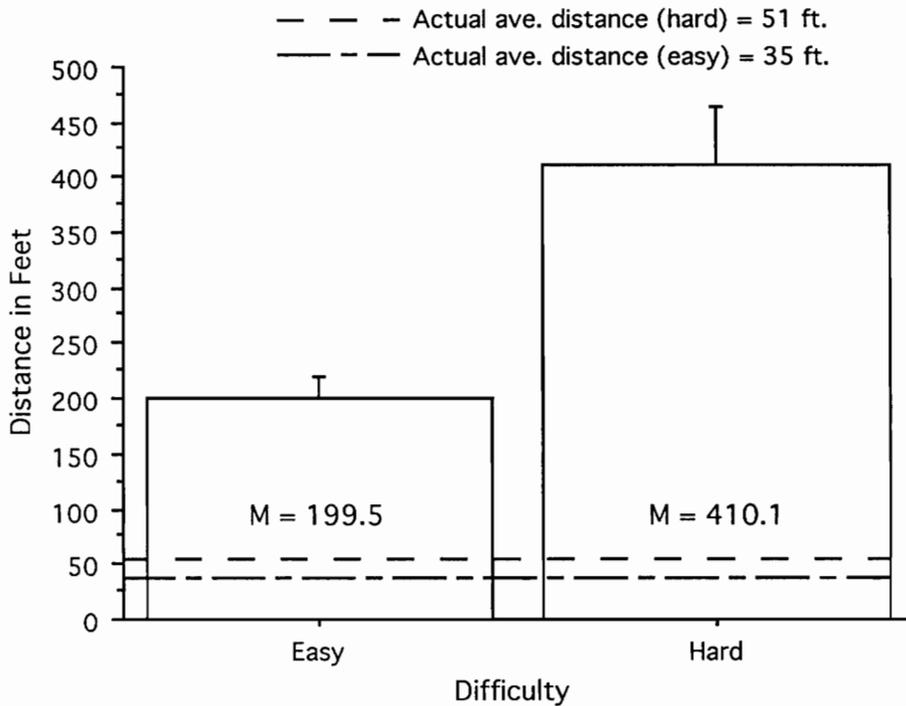


Figure 16. Mean distance estimates for VM.

and 16, distances were judged to be much farther than they actually were in both the FOV and Difficulty conditions.

Difficulty was found to interact with VM $F(1, 48) = 4.413, p = 0.0409$. Figure 17 shows the Difficulty by VM interaction. Table 4 in Appendix F lists pairwise comparisons for the Difficulty by VM interaction. Difficulty had a much greater effect when there was Low VM than when there was High VM provided in the interface. When there was Low VM, the distance estimates in the Hard Difficulty conditions were significantly farther than the distance estimates in the Easy Difficulty conditions, but when there was High VM, distance estimates were not significantly different

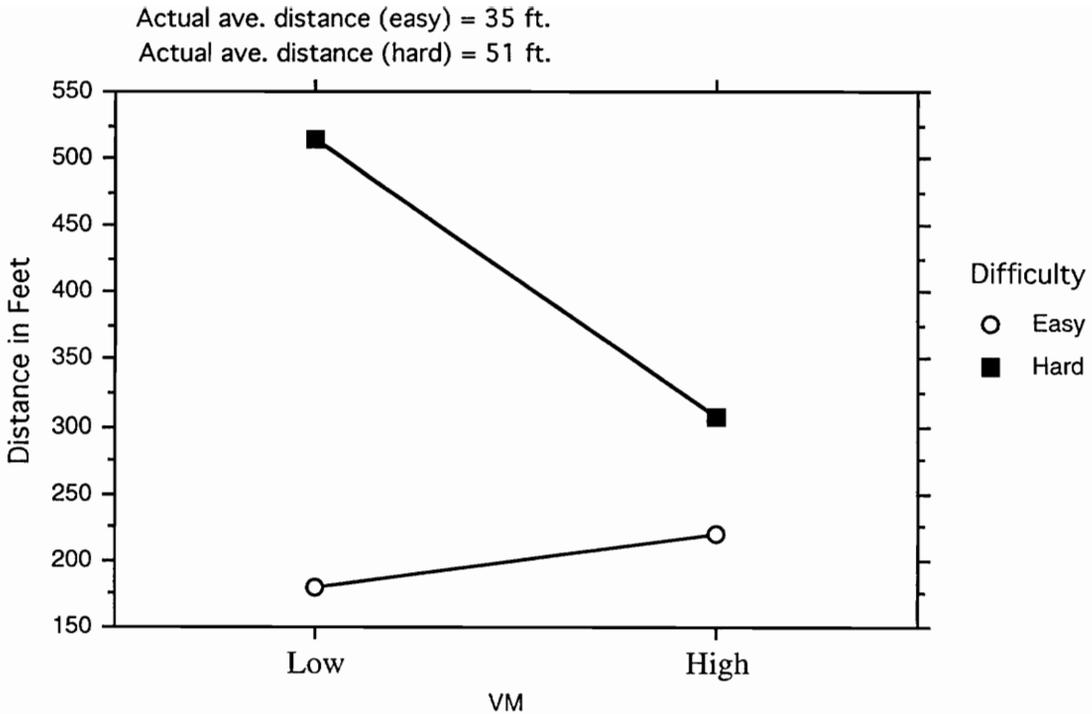


Figure 17. Interaction between Difficulty and VM for distance estimates.

between the Easy and Hard Difficulty conditions. Furthermore, the Low VM, Hard Difficulty groups estimated distances to be significantly farther than the High VM, Hard Difficulty groups.

An interaction was also found to exist between the Difficulty and FOV factors $F(2, 48) = 4.486, p = 0.0164$ (Figure 18). Table 4 in Appendix F contains the LSD test for pairwise comparisons between Difficulty and FOV. A summary of the means and standard deviations can be found in Table 5, Appendix F. As Figure 18 illustrates, the distance judgments increased for both the Easy and Hard Difficulty conditions as the FOV widened. At the 30° FOV conditions, the Difficulty factor did not make a

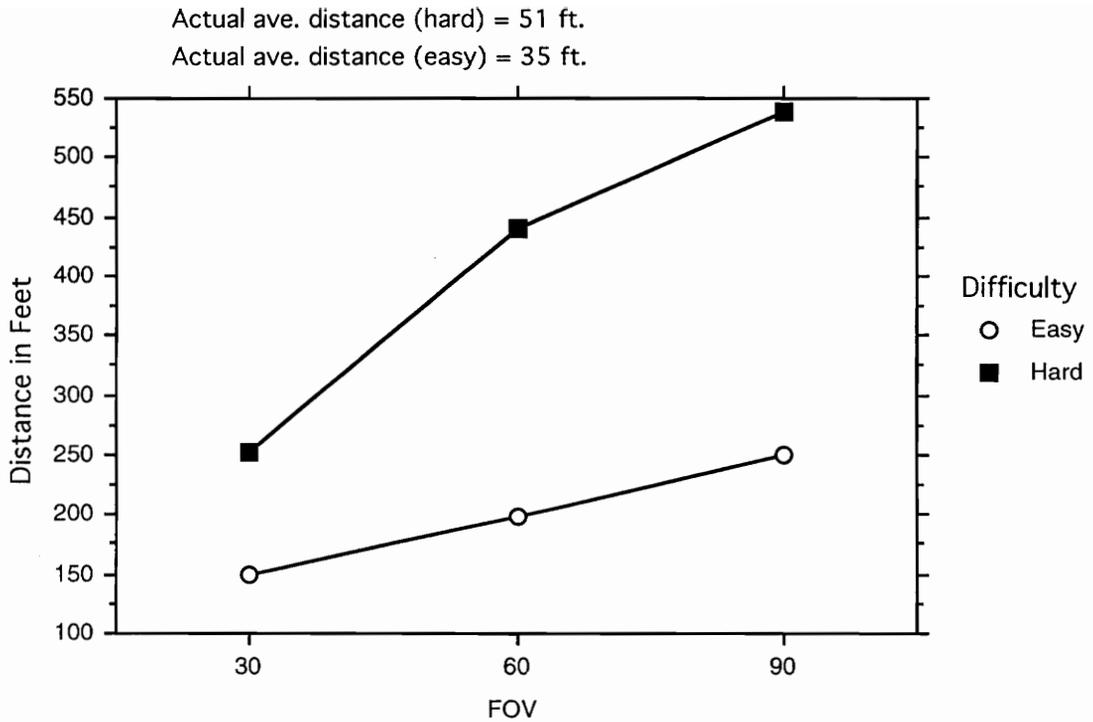


Figure 18. Interaction between Difficulty and FOV for distance estimates.

significant difference in distance judgments; however, distance estimates for the Hard Difficulty conditions were significantly larger than the Easy Difficulty conditions as the FOV increased for both the 60° FOV and 90° FOVs. Also, the Hard Difficulty, 30° FOV condition estimated distances to be significantly shorter than the Hard Difficulty, 60° FOV and Hard Difficulty, 90° FOV conditions.

Analysis of Spatial Orientation Variables

The degree of spatial orientation was analyzed from a cognitive map score, direction judgments (pointing), percent correct for object placement and time to place objects in the room reconstruct task. All of these variables are intended to be a measure of the degree to which participants were able to maintain spatial orientation while in the VE.

Analysis of cognitive map scores. The cognitive map score is a composite of scores from several characteristics of the maps. The best score that could be achieved is 46. The score total is comprised of the number of rooms and their correct placement, number of doors and their correct placement, number of hallways correctly placed, and room proportions which was a measure derived from a rating on a 1 to 5 point Likert-type scale. Two raters were used for determining map scores. Because there was a subjective component to rating room proportions, interrater reliability was established using the most preferred method, *Cohen's Kappa* (Bakeman and Gottman, 1989). The statistic examines the relationship between the proportion of actual agreement between raters and the proportion of agreement that would be expected by chance. The formula is:

$$K = P_O - P_C / 1 - P_C$$

where P_O is the actual observed agreement between raters and P_C is the expected agreement by chance. A confusion matrix was tabulated and the frequencies of agreement and disagreement were used to determine the following values:

$$K = 0.873 - 0.347 / 1 - 0.347 = 0.807$$

A *kappa statistic* of ($K = 0.807$) was found as a measure of interrater reliability. Any value of 0.7 or greater is an acceptable reliability (Bordens and Abbott, 1991).

Since there was not a significant correlation between the cognitive map score and the covariate (see Table 2 in Appendix F), an ANOVA was performed on map scores. Table 6 shows the ANOVA summary table for map scores. Table 6 in Appendix F summarizes the means and standard

Table 6. ANOVA summary table for cognitive map score.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	1440.600	1440.600	20.605	0.0001
FOV	2	24.700	12.350	0.177	0.8386
VM * FOV	2	457.900	228.950	3.275	0.0455
Residual	54	3775.400	69.915		

Dependent: Map Score

deviations for significant effects in the cognitive map score analysis.

A main effect for VM was found for cognitive map scores and is shown in Figure 19 $F(1, 54) = 20.605, p = 0.0001$. The Low VM groups scored significantly lower on cognitive map performance than the groups who had High VM.

A significant VM by FOV interaction was also found to exist for map scores $F(2, 54) = 3.275, p = .0455$. The VM by FOV interaction is presented in Figure 20. Table 7 in Appendix F summarizes the results of the LSD test for the VM by FOV interaction. When High VM was provided, map scores were significantly higher for the 30° FOV and 60° FOV conditions but not for the 90° FOV condition. In addition, the map scores in the Low VM, 30° FOV and Low VM, 60° FOV conditions were significantly lower than the Low VM, 90° FOV condition. All of the findings for cognitive map results

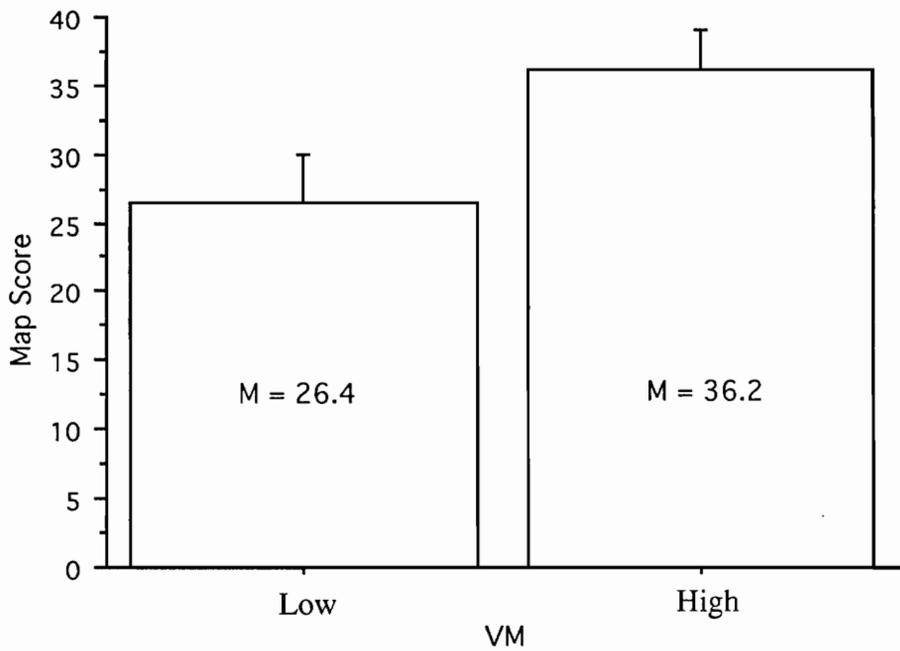


Figure 19. Overall mean map scores for VM.

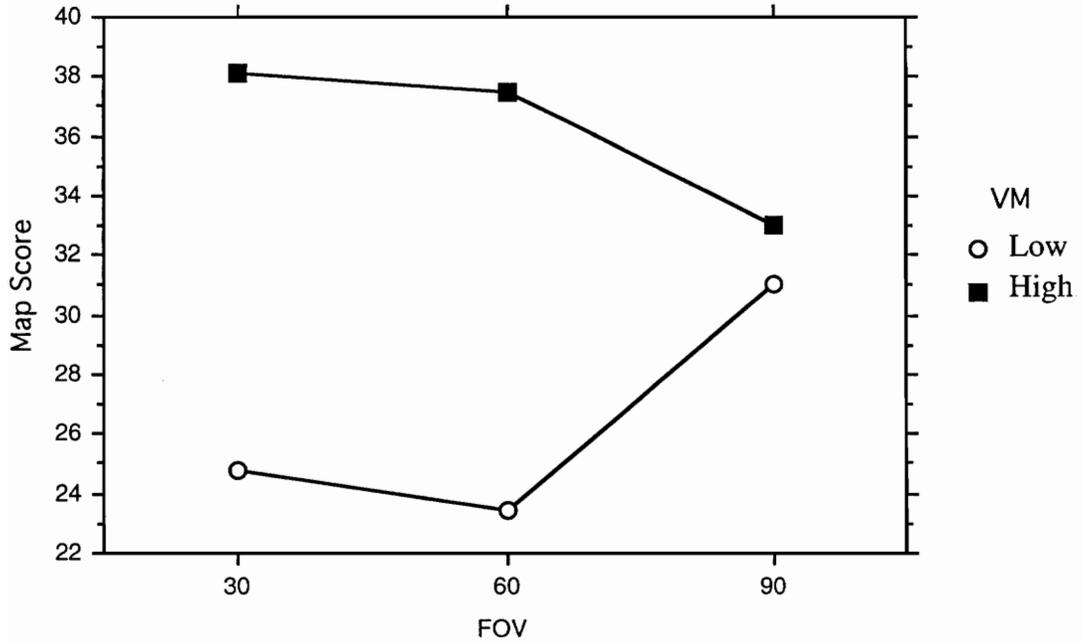


Figure 20. VM x FOV interaction for the cognitive map scores.

indicated that the higher participants scored on map tests, the more spatially oriented they were in the VE.

Analysis of direction judgments. The direction judgments were analyzed with a three-way, mixed-factor design. Difficulty was the within-factor and was determined by the difficulty of the direction judgment. Similar to the distance estimates, in the Easy conditions direction judgments consisted of pointing toward objects from the previous room visited, and in the Hard conditions judgments were made to the entrance of the building. Significant correlations were not found to exist between the covariate and direction judgments in the Easy Difficulty conditions ($R = - 0.076$) or in the Hard Difficulty conditions ($R = - 0.034$). Therefore, ANCOVA was not used in the analysis of direction judgment data. Table 7 contains the ANOVA summary table for direction judgments.

Table 7. ANOVA summary table for direction judgments

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G	H-F
VM	1	39367.519	39367.519	68.629	0.0001		
FOV	2	244.343	122.172	0.213	0.8088		
VM * FOV	2	100.475	50.238	0.088	0.9163		
Subject(Group)	54	30975.987	573.629				
Difficulty	1	1977.870	1977.870	6.980	0.0108	0.0108	0.0108
Difficulty * VM	1	1655.998	1655.998	5.844	0.0190	0.0190	0.0190
Difficulty * FOV	2	262.727	131.363	0.464	0.6315	0.6315	0.6315
Difficulty * VM * FOV	2	488.524	244.262	0.862	0.4280	0.4280	0.4280
Difficulty * Subject(Group)	54	15301.065	283.353				

Dependent: Degrees Azimuth

Epsilon Factors for df Adjustment

G-G Epsi... H-F Epsilon

Difficulty	1.000	1.094
------------	-------	-------

Both main effects of Difficulty and VM were significant $F(1, 54) = 6.980, p = 0.0108$ and $F(1, 54) = 68.629, p = 0.0001$, respectively. All significant means for direction judgments can be found in Table 8 of Appendix F. The main effect for Difficulty is shown in Figure 21. The

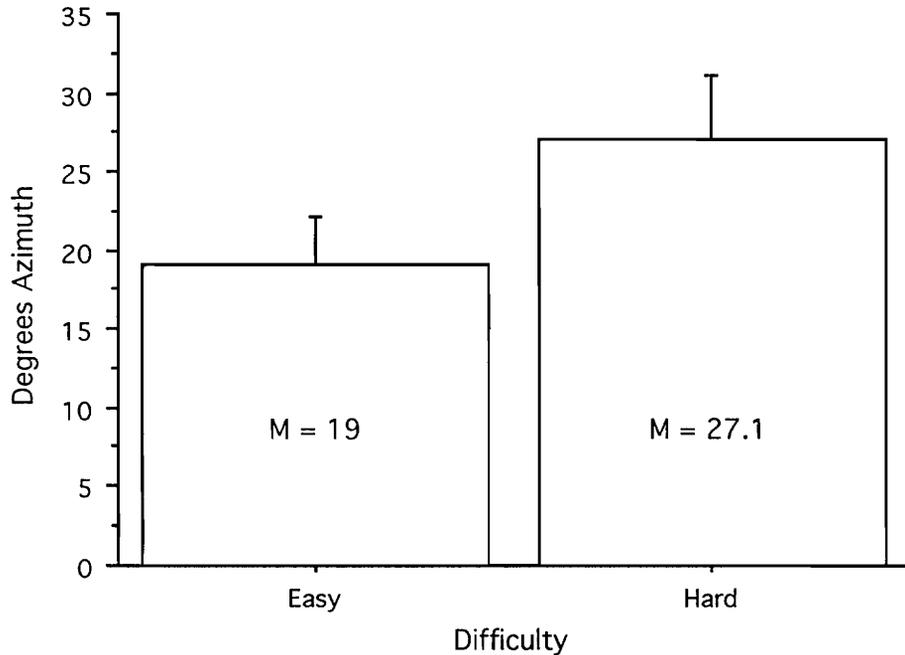


Figure 21. Mean degrees azimuth direction judgments for Difficulty.

direction judgments in the Easy Difficulty conditions have significantly less error than direction judgments in the Hard Difficulty conditions.

Figure 22 shows the main effect for VM. Direction judgment error was significantly less in the High VM conditions than in the Low VM conditions. When High VM was present, direction judgments were within a few degrees of the target ($M = 5^\circ$ azimuth).

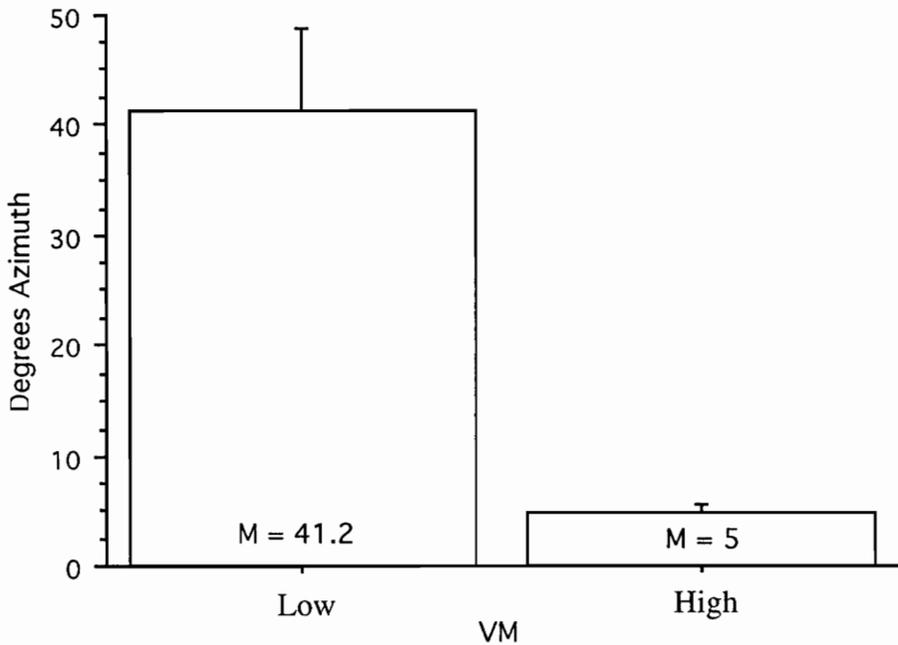


Figure 22. Mean degrees azimuth direction judgments for VM.

A significant Difficulty by VM interaction was found for direction judgments $F(1, 54) = 5.844, p = 0.0190$. Figure 23 shows the Difficulty by VM interaction. Table 9 in Appendix F lists the results of the LSD test for the Difficulty by VM interaction. When there was Low VM, there was a significant difference between the Easy and Hard Difficulty conditions. When High VM was provided, however, there was no difference between the Easy and Hard Difficulty conditions for direction judgments.

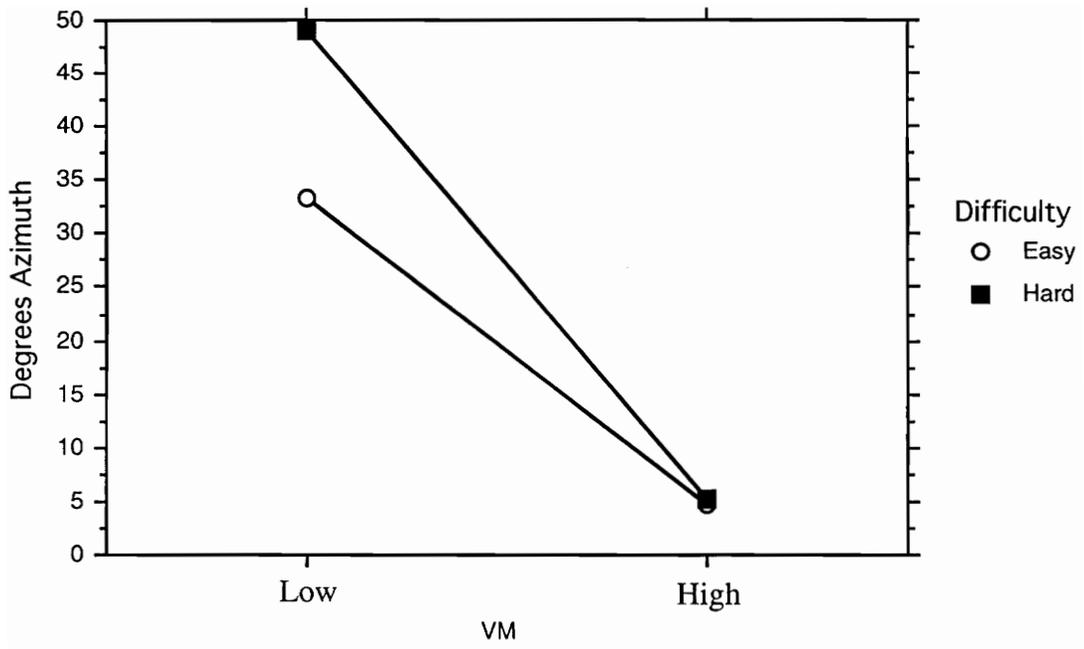


Figure 23. Interaction effect for Difficulty x VM.

Analysis of object placement error for room reconstruction. Because a significant correlation was not found between object placement error and the covariate (see Table 2 in Appendix F), ANOVA was used to analyze this variable. Table 8 shows the ANOVA summary table for object placement error. A main effect for FOV was found for object placement

Table 8. ANOVA summary table for object placement error.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	0.056	0.056	1.244	0.2696
FOV	2	0.527	0.263	5.870	0.0049
VM * FOV	2	0.209	0.105	2.331	0.1069
Residual	54	2.422	0.045		

Dependent: Percent Correct

$F(2, 54) = 5.870, p = 0.0049$. The means summary in Figure 24 shows the FOV main effect. A summary of means and standard deviations can be found in Table 10 of Appendix F. The LSD pairwise comparisons for FOV can be found in Table 11 of Appendix F. The percentage of items correctly placed was significantly less in the 30° FOV conditions than in the 60° FOV and 90° FOV conditions.

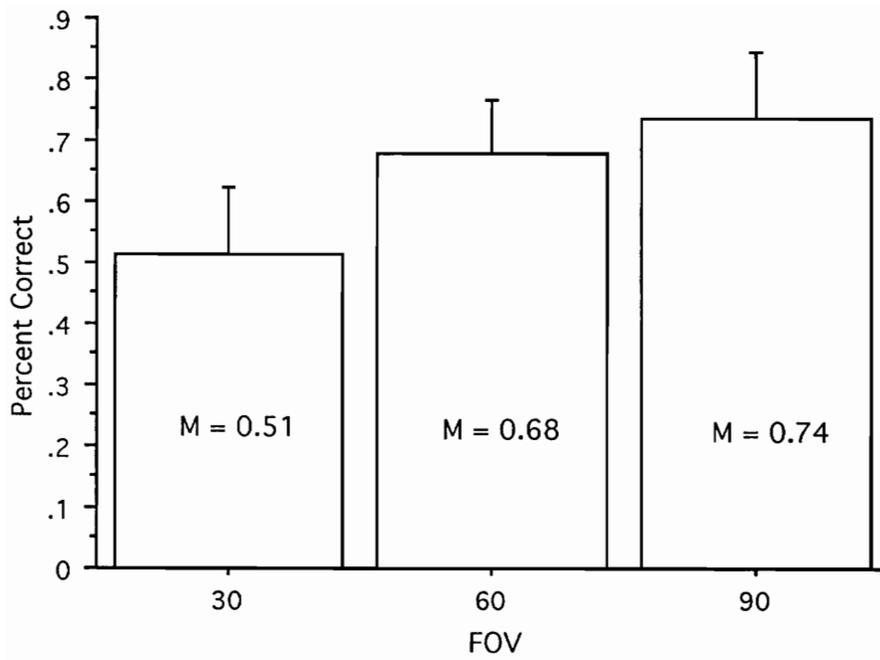


Figure 24. Mean object placement error for FOV.

Analysis on room reconstruct time. Room reconstruct time was analyzed to determine how long it took participants to place objects in their original position. Table 9 contains the ANOVA summary table for room reconstruct time. A significant main effect for VM was found for the object

Table 9. ANOVA summary table for object placement time.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	22.546	22.546	4.138	0.0469
FOV	2	20.237	10.119	1.857	0.1660
VM * FOV	2	0.662	0.331	0.061	0.9411
Residual	54	294.253	5.449		

Dependent: Time

placement time $F(1, 54) = 4.138, p = 0.0469$. Furthermore, a significant Pearson correlation coefficient ($R = -0.319$) was found to exist between object placement time and spatial ability. Therefore, an ANCOVA was performed on object placement time, and the summary is given in Table 10. Again, only a significant main effect for VM was found for the object

Table 10. ANCOVA summary table for object placement time.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	25.892	25.892	5.406	0.0243
FOV	2	6.409	3.205	0.669	0.5169
Spatial	1	22.219	22.219	4.639	0.0363
VM * FOV	2	11.101	5.551	1.159	0.3225
VM * Spatial	1	15.746	15.746	3.287	0.0761
FOV * Spatial	2	2.944	1.472	0.307	0.7369
VM * FOV * Spa...	2	11.661	5.831	1.217	0.3050
Residual	48	229.906	4.790		

Dependent: Time

placement time $F(1, 54) = 5.406, p = 0.0243$. However, the ANCOVA analysis did produce greater significance for the VM main effect. The full analysis will only be reported for the ANCOVA. The means and standard deviations summary is provide in Table 12 in Appendix F. Figure 25 shows the main effect for VM. The groups who had High VM took significantly longer to reconstruct the room layout than the groups who had Low VM.

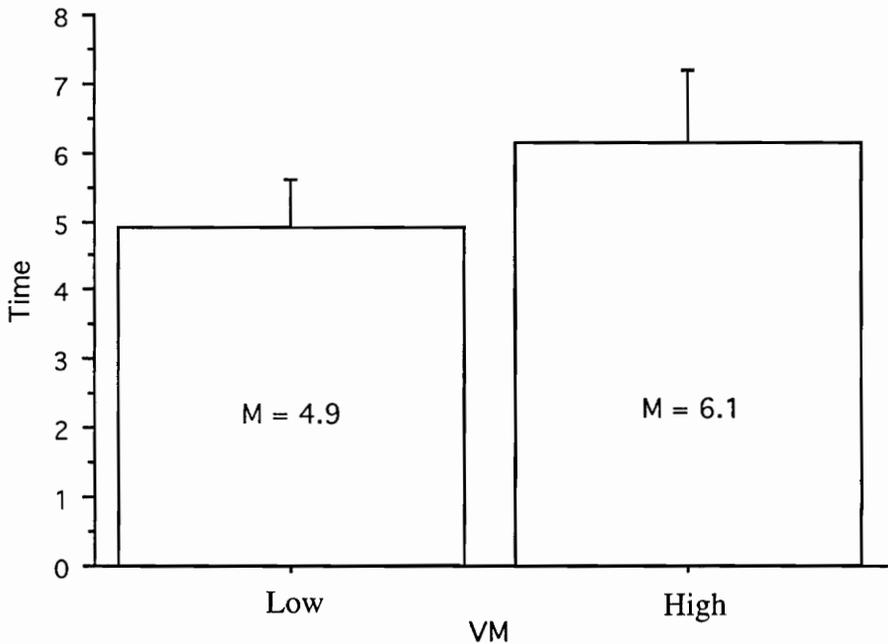


Figure 25. Mean time to reconstruct the room layout for VM.

Analysis of Questionnaire Responses

The questionnaire results reported in this section are derived from the responses to the post-test questionnaire in Appendix A. Nine questions were given and each used a balanced seven point Likert-type rating scale. None of the questions were significantly correlated with spatial ability. An ANOVA was performed on the Question 1, "How easy/difficult was it to navigate through the virtual environment?" Table 11 shows the summary table for the ANOVA. The VM main effect is significant $F(1, 54) = 4.737$,

Table 11. ANOVA summary table for Question 1.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	6.667	6.667	4.737	0.0339
FOV	2	0.833	0.417	0.296	0.7449
VM * FOV	2	6.433	3.217	2.286	0.1115
Residual	54	76.000	1.407		

Dependent: Rating

$p = 0.0339$. The means summary table is provided in Table 13 of Appendix F, and the main effect is shown in Figure 26. The High VM groups rated navigating through the virtual environment to be significantly easier than did the Low VM groups.

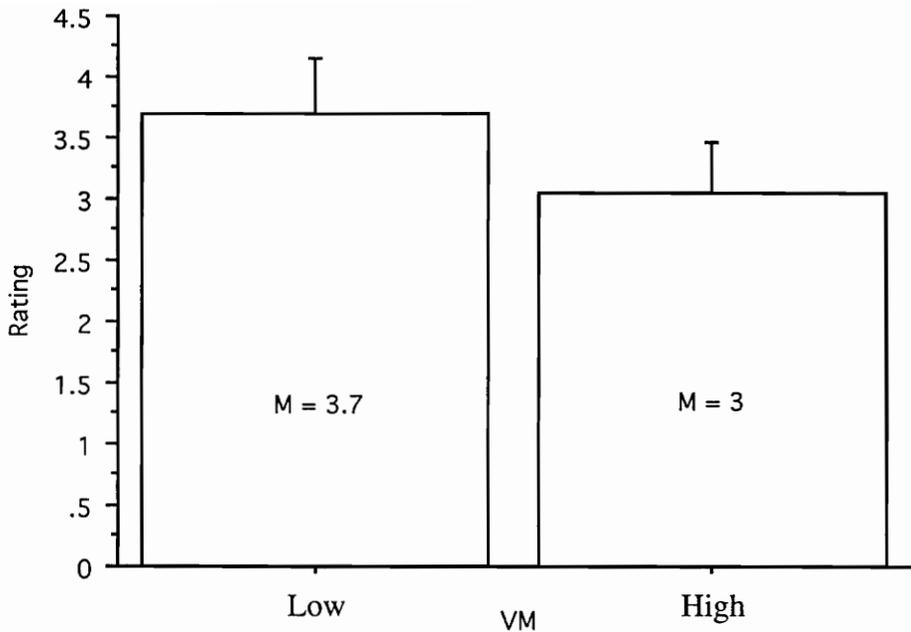


Figure 26. Mean ratings for Question 1.

Questions two through five were not found to be significant across groups. Their ANOVA summary tables are presented in Appendix F.

- 2) How unrestrained/restrained did you feel when navigating through the virtual environment? (Table 14)
- 3) How proportional/unproportional did the space in the virtual environment appear? (Table 15)
- 4) How real/phony did the virtual environment feel? (Table 16)
- 5) How roomy/cramped did the virtual environment feel? (Table 17)

An ANOVA was performed on Question 6, "In general, how sure/unsure were you about making room dimension estimates?." There was a significant main effect for FOV $F(2, 54) = 5.449, p = 0.0070$ and for the VM by FOV interaction $F(1, 54) = 5.598, p = 0.0062$. Table 12 shows the ANOVA summary table. The means and standard deviations for significant

Table 12. ANOVA summary table on Question 6.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	5.400	5.400	3.455	0.0685
FOV	2	17.033	8.517	5.449	0.0070
VM * FOV	2	17.500	8.750	5.598	0.0062
Residual	54	84.400	1.563		

Dependent: Rating

effects are in Table 18 of Appendix F. The FOV main effect is shown in Figure 27. The LSD test results are also listed in Table 19 of Appendix F. The 60° FOV groups were significantly more sure about making room dimension estimates than the 90° FOV groups. The VM by FOV interaction is shown in Figure 28. Table 19 in Appendix F shows LSD tests for all significant effects found for Question 6. A lower rating indicates that participants were more sure about estimating room dimensions. For the 30° FOV and 60° FOV conditions, the Low VM groups were significantly less sure about making room dimension estimates than the same groups with High VM. However, for the 90° FOV groups, the ratings reversed, but there were no significant differences between the Low VM and High VM groups. Also, the High VM, 30° FOV and High VM, 60° FOV conditions were

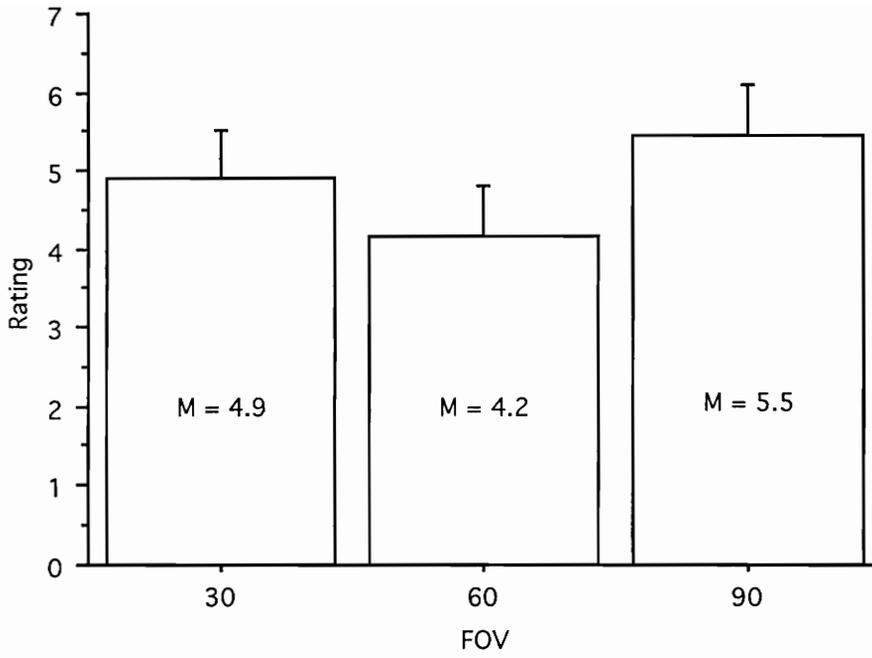


Figure 27. Mean ratings for the FOV main effect on Question 6.

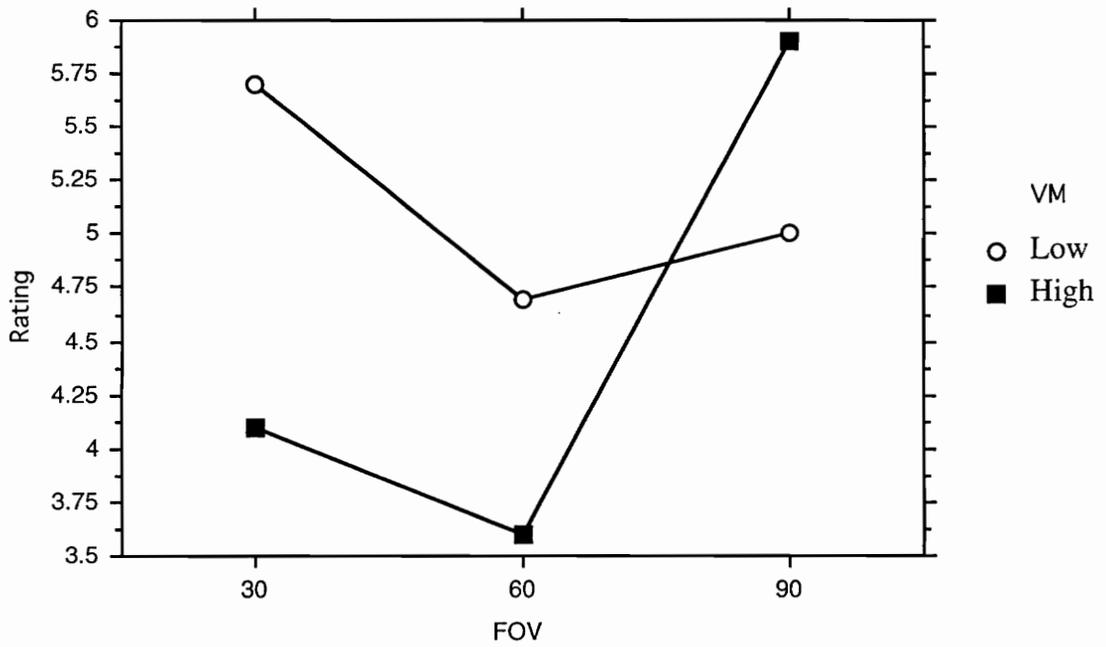


Figure 28. The VM x FOV interaction for Question 6.

significantly more sure about estimating room dimensions than the High VM, 90° FOV conditions.

An ANOVA was conducted on Question 7, "In general, how sure/unsure were you about making direction judgments to objects from the previous room?" Table 13 shows the ANOVA summary table. A main

Table 13. ANOVA summary table for Question 7.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	45.067	45.067	26.920	0.0001
FOV	2	5.733	2.867	1.712	0.1901
VM * FOV	2	5.733	2.867	1.712	0.1901
Residual	54	90.400	1.674		

Dependent: Rating

effect was found for VM $F(1, 54) = 26.920, p = 0.0001$. The means and standard deviation summary for VM are presented in Table 20 of Appendix F, and the main effect is shown in Figure 29. The groups with High VM rated their sureness significantly higher for direction judgments than the Low VM groups.

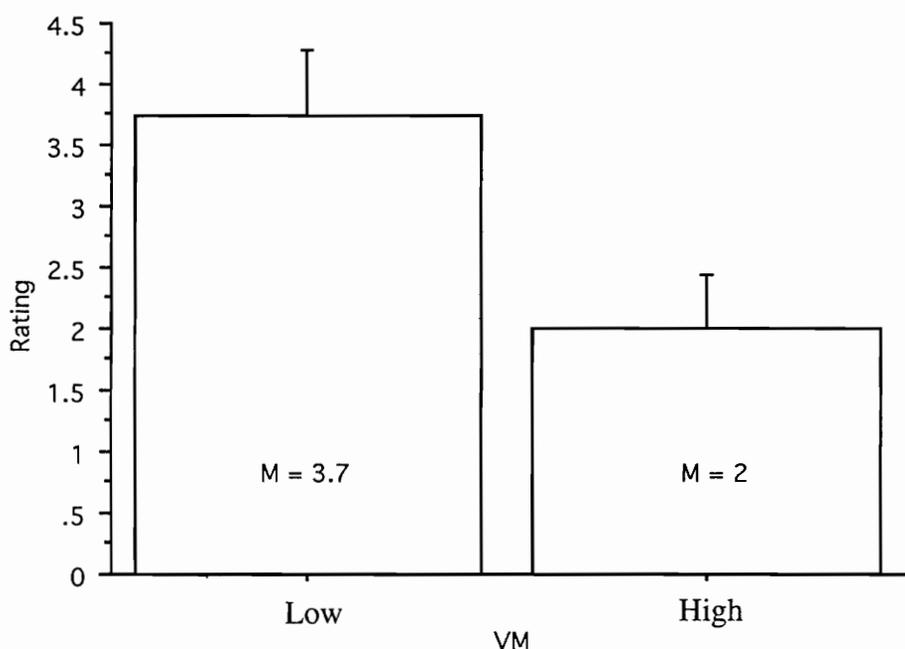


Figure 29. Means for the VM main effect on Question 7.

An ANOVA was performed on Question 8, "In general, how sure/unsure were you about making direction judgments to the entrance?" Table 14 shows the ANOVA summary table. A significant main effect for

Table 14. ANOVA summary table for Question 8.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	126.150	126.150	54.628	0.0001
FOV	2	2.800	1.400	0.606	0.5491
VM * FOV	2	1.200	0.600	0.260	0.7721
Residual	54	124.700	2.309		

Dependent: Rating

VM was discovered $F(1, 54) = 54.628, p = 0.0001$. Table 21 in Appendix F

contains the means summary for VM. The main effect for VM is shown in Figure 30. Similar results to question seven were found. The groups with

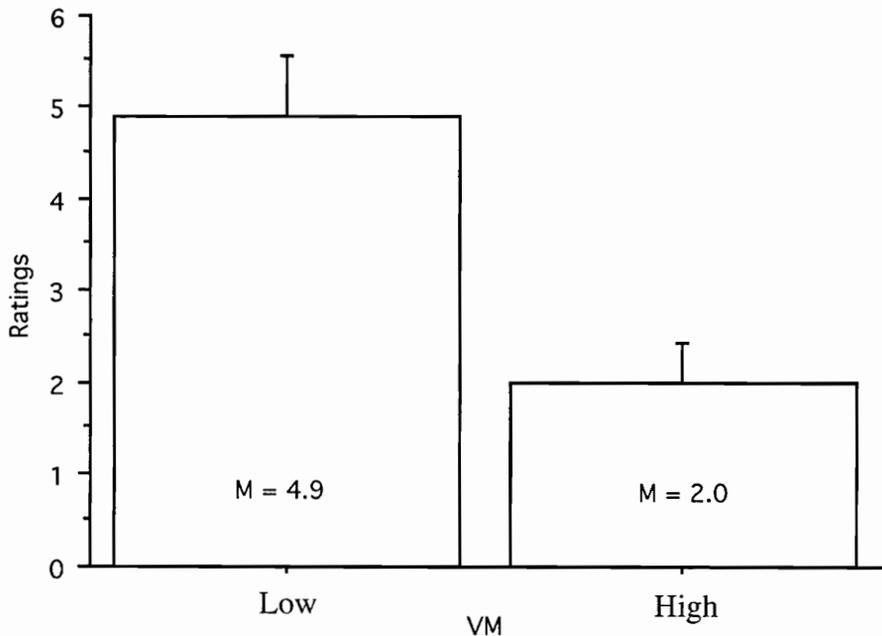


Figure 30. Means for the VM main effect on Question 8.

High VM rated their sureness significantly higher for direction judgments to the entrance than did the Low VM groups.

Finally, an ANOVA was conducted on Question 9, "In general, how good/poor do you think your mental map of the virtual environment is?" Table 15 shows the ANOVA summary table. A significant main effect for VM $F(1, 54) = 54.628, p = 0.0001$ and for the VM by FOV interaction $F(1, 54) = 54.628, p = 0.0001$ was found for ratings on Question 9. Figure 31 shows the main effect for VM. The High VM groups rated their mental maps to be significantly better than did the Low VM groups. Table 22 of Appendix F shows the means and standard deviations for all significant

Table 15. ANOVA summary table for Question 9.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	12.150	12.150	5.330	0.0248
FOV	2	0.700	0.350	0.154	0.8580
VM * FOV	2	19.300	9.650	4.233	0.0196
Residual	54	123.100	2.280		

Dependent: Rating

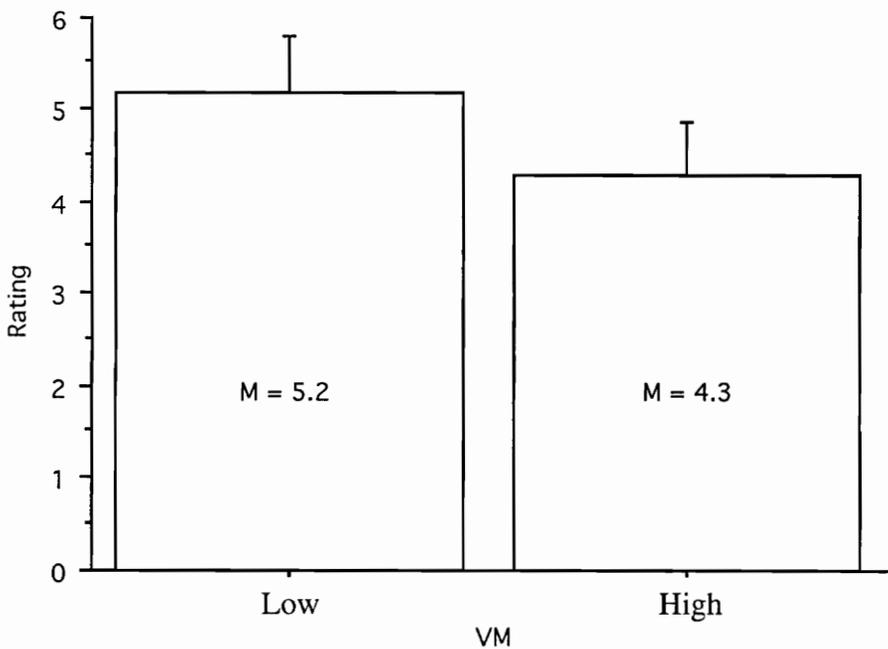


Figure 31. Means for the main effect of VM on Question 9.

effects in Question 9. Figure 32 shows the VM by FOV interaction. The LSD test for the VM by FOV interaction is presented in Table 23, Appendix F. Having High VM significantly affect ratings for the 30° FOV and 60° FOV groups but not for the 90° FOV groups. The High VM, 30° FOV and High VM, 60° FOV groups rated their cognitive maps to be significantly better than did the Low VM, 30° FOV and Low VM, 60° FOV groups,

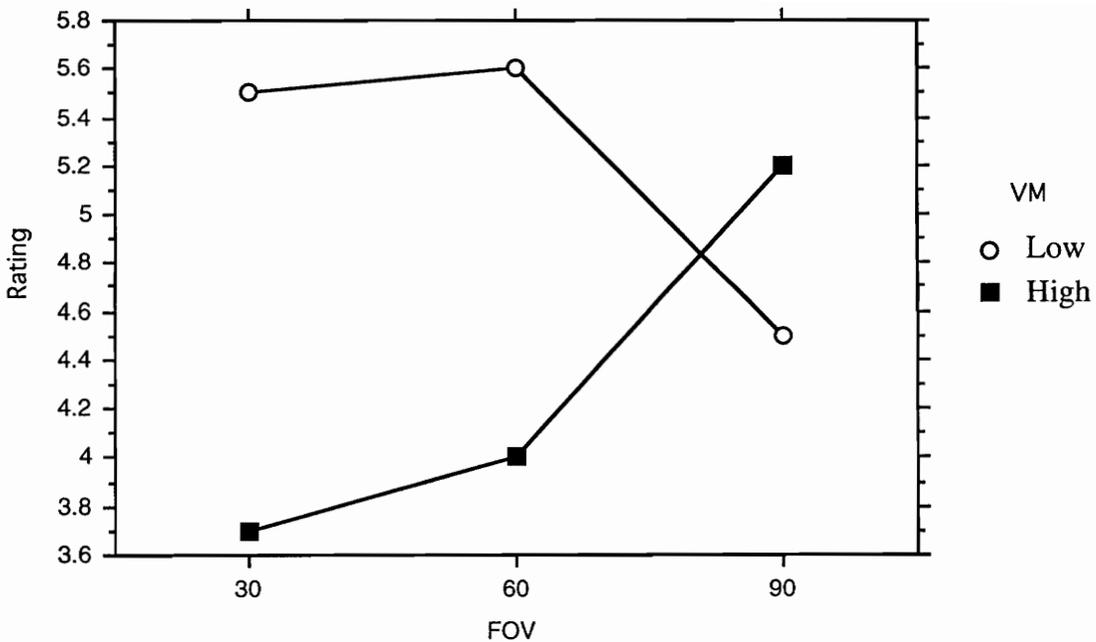


Figure 32. VM x FOV interaction for Question 7.

respectively. However, there were no significant differences between the Low VM, 90° FOV and High VM, 90° FOV groups.

Analysis of Correlations

Correlations were calculated between the following variables:

Dependent variables

- Room size estimates and distance estimates to objects
- Room size estimates and distance estimates to the entrance
- Cognitive map scores and degrees azimuth to objects
- Cognitive map scores and degrees azimuth to the entrance

Dependent variables and questionnaire responses

- Room size estimates and sureness of estimating room sizes (Question 6)

- Degrees azimuth to objects and sureness of estimating direction to objects (Question 7)
- Degrees azimuth to the entrance and sureness of making direction judgments to the entrance (Question 8)
- Cognitive map scores and the perceived goodness of participants' mental map (Question 9)

All correlations were calculated with the Pearson correlation coefficient (R). Table 24 in Appendix F shows all the correlations for the variables outlined above and their corresponding confidence intervals.

There is a significant correlation between room size estimates and distance estimates to objects from previous rooms ($R = 0.841$) and distance estimates to the entrance ($R = 0.767$). As room size estimates increased so did distance estimates to objects and the entrance.

Cognitive map performance was predicted to be significantly related to direction judgments because both are expected to reflect the participants degree of spatial orientation. Cognitive map performance shows a significant negative relationship for direction judgments to objects ($R = -0.434$) and direction judgments to the entrance ($R = -0.591$). As cognitive map performance increased, indicating a greater spatial awareness, the error decreased in degrees azimuth for direction judgments, which also indicates increased spatial orientation.

A significant correlation was not found between room size estimates and how sure participants responded they were about making room dimension estimates. As room size estimates varied, participants did not feel

strongly either way about how sure they were of their estimates. Direction judgments in degrees azimuth to objects is significantly correlated ($R = -0.372$) with how sure participants were about their direction judgments (Question 7). When error decrease in direction judgments to objects, they were less sure of their judgments. As would be expected, however, as error in direction judgments to the entrance decreased, participants were more sure of their judgments ($R = 0.829$). Lastly, cognitive map scores and how well participants responded that they thought their mental map reflected the VE was significantly correlated ($R = -0.619$). As the map scores increased, reflecting a greater degree of spatial orientation, participants responded that they were more sure their mental maps reflected the VE.

DISCUSSION

This research focused on the perceptual and cognitive performance of participants in desktop VEs as it relates to two general issues: (1) the perception of basic space dimensions and (2) spatial representation and orientation. Also considered were individual differences in participants spatial ability. For purposes of this discussion, the distinction between GFOV and FOV in this study needs to be explained. Manipulating the GFOV has two consequences for desktop VEs: (1) it causes distortions in the image because of changes in perspective, and (2) it creates the amount of VE visible at one time, which is the FOV for the desktop VE. Therefore, when discussing variables in this experiment that relate to distortions in the images (e.g., room sizes), GFOV will be the term used. When discussing variables from this experiment, however, that relate to the amount of visible space in the VE (e.g., cognitive map), FOV will be the term used.

Performance with Basic Space Dimensions

Room size estimates. Room size estimates in the VE were shown to be sensitive to both VM and GFOV factors. These findings, however, were directly dependent on spatial ability. Before spatial ability was factored into the analysis, space dimension estimates were not shown to be dependent on VM and GFOV influences. It is not immediately evident that spatial ability would influence the ability to estimate distances—spatial ability is usually associated with spatial orientation and navigation. Although, if one considers that humans' normal FOV is approximately 200°, and distance estimates in this experiment were being made with less than half of that (30°, 60°, 90°), it is possible that participants were having to rely on spatial

information integration while estimating distances. After all, participants were never able to see the majority of the room in a single 3D view, even with the 90° GFOV. Alfano and Michel (1990) have clearly shown that peripheral information in humans' FOV and its overlap are necessary to form an accurate representation of the world.

Considering performance just across the three GFOV conditions, the 60° GFOV and 90° GFOV groups were within 20 square feet of estimating the actual room dimensions, while the 30° GFOV conditions underestimated the space by an average of over 300 square feet. In addition, the Low VM, 60° GFOV and High VM, 60° GFOV conditions were the most accurate at estimating room dimensions. However, the Low VM, 30° GFOV and High VM, 30° GFOV conditions greatly underestimated room dimensions. The telephoto bias described by Roscoe (1984) and referred to as the virtual space effect by McGreevy and Ellis (1986) was certainly replicated in this experiment. These findings suggest that 60° is an optimum GFOV for perception of space characteristics in perspective displays. McGreevy and Ellis (1986) and Barfield et al. (1990) also found approximately 60° GFOV to result in optimum performance for making perceptual judgments in perspective displays. The fact that their findings were for exocentric judgments (judgments between two objects), and the findings in this study were for egocentric judgments, suggests that the 60° GFOV optimum is robust across a range of perceptual tasks in perspective displays. Furthermore, Osgood and Wells (1991) found the performance in a HMD was significantly better when the FOV was 40° or larger.

For Question 6, how sure participants were about making room dimension estimates, the 60° GFOV groups were significantly more sure about making dimension judgments than the 30° GFOV and 90° GFOV groups. This result is consistent with the accuracy of performance and with the conclusion that 60° is the optimal GFOV for space dimension estimates. The findings for the VM by GFOV interaction for Question 6 directly reflected performance in the VM by GFOV interaction for room dimension estimates. The subjective responses demonstrated that participants were aware of how well they were performing.

When looking at room dimension estimates for just the High VM versus Low VM conditions, room dimension estimates were significantly better when High VM was provided in the interface. The actual average square footage of rooms was 676.5 square feet. The average room size estimates for Low VM groups was ($M = 495.6$) while the High VM groups on average came within 25 square feet of estimating the dimensions correctly ($M = 651.3$). This shows that High VM across all groups was successful as a symbolic enhancement for improving the perception of space in the VE. Because of the restricted GFOVs, participants were required to use a number of 3D views to estimate room dimensions, and VM improved the integration and extraction of information across those views by providing an accurate and consistent model of the VE.

VM had less of an effect on the 30° GFOV and 60° GFOV room size estimates, but greatly impacted the 90° GFOV conditions. High VM for the 90° group caused participants to overestimate the room dimensions by more than an average of 200 square feet. When the environment was viewed with

a 90° GFOV and Low VM, participants underestimated the dimensions by little less than 200 feet.

Clearly across all groups, VM is impacting perception of the space. When High VM was provided, the room estimates steadily increased as the GFOV increased with the High VM, 60° GFOV being closest to actual room sizes. It appears across all six conditions of VM and GFOV, High VM increased room size estimates. And in the High VM, 90° FOV condition, VM was actually detrimental due to the participants overestimating the size of the space.

It should also be pointed out that the variability for estimating dimensions was very high for all the groups. It is important to note that providing High VM did not reduce that variability. It could be expected that having an overview map showing the relative proportions between rooms would have given participants some common ground to base their judgments even though no actual dimensions were available on the map. One conclusion that can be drawn is that even though the effect of VM influenced the perception of space, participants were still overwhelmingly focusing on the 3D view which biased their judgments depending on the GFOV.

Distance estimates. Distance estimates to objects that were out of view during the judgment, but which had been previously viewed, produced some of the effects similar to room size estimates. The Difficulty factor was manipulated for distance estimates by how recently the object had been viewed before the distance judgment was required. The remarkable finding in these judgments is that distance was dramatically overestimated in all the

conditions, exceeding almost 500 feet in some cases. This effect may be better explained in the next section by conceptualizing distance judgments to unseen targets as a measure of spatial orientation. However, it is still useful to consider these findings in the context of perception based on the basic space characteristics of desktop VEs.

The telephoto effect caused by a restricted GFOV was again shown to produce perceptual errors. The 30° GFOV conditions estimated distances to be significantly shorter than the 60° GFOV and 90° GFOV conditions. Also, the Hard Difficulty, 30° GFOV conditions estimated distances to be significantly shorter than the Hard Difficulty, 60° GFOV and Hard Difficulty, 90° GFOV conditions. It's difficult, however, to suggest what the best GFOV is for making distance estimates to unseen targets because all the distance estimates were so greatly over exaggerated. It would probably be in error to suggest that because the 30° GFOV distance estimates were closer to the actual dimensions than the other two larger GFOVs that a 30° GFOV is the best for making these kinds of perceptual judgments. Clearly, the telephoto effect occurred across the three GFOVs, but distance judgments overall occurred on an inflated scale well above actual distances. Before any conclusions can be drawn regarding distance estimates and GFOV, the other factors should be considered for this variable.

Distance estimates were significantly shorter in the Easy Difficulty conditions than in the Hard Difficulty conditions. Although, distance estimates in both conditions were greater than the actual distances. However, High VM significantly improved distance estimates for the Hard Difficulty conditions. Distance estimates in the Hard Difficulty conditions

were significantly shorter when High VM was available than when it was not. When High VM was available, there were no significant differences between the Easy and Hard Difficulty distance estimates. However, when High VM was not available in the interface, distance estimates were significantly farther in the Hard Difficulty conditions than in the Easy Difficulty conditions. There were no significant differences between the Easy Difficulty distance estimates for the Low VM and High VM conditions. This finding effectively demonstrates that High VM is more beneficial as the task difficulty increases for distance estimates to unseen targets.

What is most surprising is that even when participants were estimating room dimensions correctly, they were greatly overestimating distance judgments to unseen targets. In fact, when they had the overview map which was proportionally correct in scale, they did not appear to be using it and their associated room estimates to aid them in distance estimates to objects that could not be seen in the 3D view. This suggests that subjects were overwhelmingly biased by the 3D view and were unable to integrate the information across the egocentric and exocentric views as far as distance estimates to unseen targets were concerned. This may have resulted more because of the spatial orientation required, which imposed additional constraints on the task of estimating distance to unseen targets.

Room size estimates were significantly correlated with distance estimates in both the Easy and Hard Difficulty conditions. As room size estimates increased so did distance estimates. These findings are consistent

with the telephoto bias shown to occur with GFOV manipulations in perspective displays.

Spatial Representation and Orientation

Distance estimates. It may be useful to view distance estimates to unseen targets as a measure of spatial orientation because navigation was required between the time they viewed the target and the time they made the distance judgment. The more spatially oriented the participants were while navigating between the two points, the greater their understanding should be for the distance between their position and the target.

The distance estimates in the Easy Difficulty conditions were less than half of what was estimated in the Hard Difficulty conditions. These results are consistent with previous findings. Wells and Venturino (1989) and Wells et al. (1989) found that performance losses as the result of restricted FOV were dependent on task difficulty. Task difficulty requires a greater degree of spatial information integration and places additional memory and attentional resource demands on users.

FOV also interacted with Difficulty. Increased FOV restriction was significantly more detrimental to distance estimates in the Hard Difficulty conditions than in the Easy Difficulty conditions. However, FOV restriction decreased and task Difficulty increased distance judgments. Recall that all the distance estimates were greatly overestimated. This suggests from the findings that, as where task Difficulty decreased spatial awareness, FOV restriction increased spatial awareness. One may be inclined to conclude that because distance estimates increased with larger FOVs, and because these increases continued to be larger than actual distances, participants were

less spatially oriented as FOV increased. This conclusion would be in direct contradiction to all of the previous findings in the real-world and in simulated environments (Alfano and Michel, 1990; Dolezal, 1982; Hagen et al, 1978; Osgood and Wells, 1991; Venturino and Wells, 1990; Venturino and Kunze, 1989; Wells et al., 1988; Wells and Venturino, 1989) and from the findings in this study based on the cognitive map and object placement variables.

One plausible explanation for this apparent contradiction is that the participants were using their current visible portion of the environment (the room they were in) to base the distance to the unseen targets and this biased their judgments for distances. Over estimates did occur for wider FOVs in room size estimates. As discussed previously, however, these distance estimates were exaggerated even when participants were provided with High VM. In some cases they estimated room sizes correctly, could see the distances they estimated correctly in the overview map (room(s) between their position and the unseen target), but still greatly overestimated the distance when the target could not be seen in the 3D view.

Research has shown that, in general, people are not very good at assigning units to absolute distances (Passini, 1992). Certain consistent distortions in distance estimates have been shown to occur. Canter (1977) and Byrne (1979) have demonstrated that routes are perceived to be longer if there are more intersections, barriers, curves, or reference points occurring along the path. Furthermore, Hartley (1977) referred to intervening points on a route increasing distance estimates as the "clutter effect." These findings were supported from the results of this study. The Difficulty factor

showed that as the number of intervening points increased between the time the participant viewed the object and the time the estimate was given, a greater increase (error) in distance estimates occurred.

Even if one was to suggest that the lack of textures and other detail in the VE contributed to distance traveled misperception, it is unlikely that these factors would solely contribute to such gross over estimation, especially considering the aid of an overview map. In this case, distance estimates to unseen targets was probably not a good measure of spatial orientation because participants with High VM clearly understood the spatial relationships between their position and the object. Distance estimates have been shown to be a useful measure of spatial familiarity with real environments (Gordon et al., 1989; Kosslyn, et al., 1974; Lindberg and Garling, 1981), but this measure may have to be reassessed for desktop VEs.

In summary, increases in FOV increased distance estimates, and these increased distance estimates occurred more in the Hard Difficulty conditions than in the Easy Difficulty conditions. Increases in task difficulty also increased distances estimates. Although, High VM did decrease distance estimates for the Hard Difficulty conditions. Because all distance estimates were farther than actual distances, any increase in distance estimates is also an increase in error. As discussed above, people are very poor at estimating distances from a route they have traveled. It appears that in this experiment for a desktop VE, in terms of the actual distances, a floor effect occurred for distance estimates. None of the conditions were able to accurately estimate distances. Furthermore, because some of the estimates were to objects viewed from the previous room (a relatively simple task), an extremely

simple task would be required to increase the sensitivity of the measure enough to detect any differences in participants' ability to estimate distances in the VE. Based on the findings in this study, people are apparently very poor at judging distances to objects based on a route they have traveled in a VE. It is suspected that these judgment errors are considerably worse than would occur in a real environment. Also, although High VM did provide some improvement for distance estimates in the Hard Difficulty conditions, it was unable to completely overcome the distortions in participants' spatial representation relating to distance estimates to unseen targets across the majority of conditions in the study.

Several conclusions can be drawn about distance estimates and the independent variables. Even in the 30° FOV conditions, distance estimates were overestimated by nearly 200 feet. And as FOV increased to 60° and then 90°, distance estimates almost increased a 100 feet per each increase in FOV. In light of the optimum 60° GFOV recommended for space perception based on room size estimates, and based on the 90° FOV recommendation for facilitating spatial orientation given in the next sections, it is not recommended that a 30° FOV or smaller be used to improve distance estimates. Instead, it is recommended that symbolic enhancements be used to facilitate users' spatial representation relating to distances. However, clearly more is needed than landmarks and an overview map without any dimensions on it like the one used in this study. The possibilities are almost endless for providing distance information in VEs. What is important to note is that because of other considerations, mainly the basic perception of space and spatial orientation, methods other than FOV or

VM, as applied in this study, must be used to overcome the distortions that occur in peoples' cognitive maps for distances traveled.

Cognitive map. Spatial orientation has long been considered to be based on the ability of humans to integrate spatial information from the environment into a mental map or simplified model of the world (Gordon et al, 1989; Levine et al., 1982; Passini, 1984; Tolman, 1948). The cognitive map task in this experiment was intended to measure the degree to which participants developed an accurate spatial representation of the VE. The High VM groups scored significantly higher on the map test than the Low VM groups. This difference was significantly higher for the 30° FOV and 60° FOV groups than for the 90° FOV groups. These findings are consistent with results from the real-world, fully immersive VEs, and from perspective displays. The ability to develop a cognitive map is impaired by the reduction of peripheral information and the reduction in information overlap between successive FOVs (Dolezal, 1982). High VM was successful at improving map scores for the smaller FOVs by supplementing the poor formulation of the participants' spatial model due to restricted FOVs. VM made less of a difference for the 90° FOV because the Low VM, 90° FOV group improved significantly due to the larger FOV afforded.

These results suggest that High VM, and in particular the long shot and salient landmarks, can be very successful at improving peoples' spatial representation of VEs. And this improvement, will be more substantial as the FOV is further restricted. Responses from participants regarding how well they thought their mental map reflected the VE correlated with cognitive map scores. Participants responded that their mental maps of the

VE were better as their scores on the maps increased. In addition, participants were more sure when they had High VM than when they did not, and their performance accurately reflected these impressions.

Because the Low VM, 90° FOV condition scored significantly higher on the map test than the Low VM, 30° FOV and Low VM, 60° FOV conditions, a 90° FOV or larger is recommended for facilitating spatial representation and orientation in VEs. Based on the findings, however, larger FOVs are less of a concern if the types of VM provided in this experiment are available in the VE because participants' cognitive maps were significantly better when they had High VM; in fact, their performance exceeded all of the Low VM groups.

Direction judgments. Pointing in the direction of unseen targets has been shown to be a sensitive measure for the degree of spatial orientation in real and simulated environments. As discussed earlier, spatial orientation performance is susceptible to influences of task difficulty. Direction judgments in this study were also found to be task dependent. Direction judgments in the Easy Difficulty conditions had significantly less error than direction judgments in the hard Difficulty conditions. In addition, direction judgments had significantly more error in the Hard Difficulty conditions when there was Low VM. When there was High VM, there was no difference between the two levels of Difficulty for the direction judgments. All the direction judgments in the High VM conditions were within a few degrees azimuth of the target. However, the Low VM conditions averaged over 40° azimuth error to the target. Clearly, High VM overwhelmingly improved direction judgments. This is not surprising since High VM

afforded participants an overview map containing summary information about their present position in relation to the target.

Direction judgments were not found to be significantly impacted by manipulations in FOV. And although errors in direction judgments were quite large with there being considerable differences between groups, within-group variability was very high. It appears that when VM is not provided, people are very poor at direction judgments in perspective displays and there is a large range in their performances. Wells et al. (1988) and Venturino and Wells (1990) found that the search time of participants to point to the location of previously memorized targets was sensitive to FOV. Time increased as the FOV was reduced. However, error for replacing the targets was unaffected by FOV. These findings and the results from this study suggest that if the targets are mapped into a spatial representation, finding them should not be impaired by FOV changes. Because participants in this study were so poor at direction judgments in all the FOVs without High VM, subjects in all probability did not map the spatial relationships into memory for any of the three FOVs. This was compounded by the large variability within groups. It is important to note that this measure was not influenced by participants' spatial ability scores. Therefore, no within-group variability could be pulled out of the analysis. A more sensitive measure of direction judgment may be correlated with spatial ability.

Participants responded that they were less sure about direction judgments in Easy Difficulty conditions. This is a puzzling finding since it would be expected that as error decreased, participants would be more sure of their judgments. However, as would be expected, as error decreased for

direction judgments in the Hard Difficulty conditions, participants were more sure of the judgments. Although it may be expected that the task error should have corresponded with how sure participants were about making the judgments, the level of difficulty contrast between the Easy and Hard Difficulty conditions may have biased participants into thinking that regardless of how they performed, overall they were less sure of direction judgments in the Hard Difficulty conditions. Their performance reflects this in that they performed significantly poorer in the Hard Difficulty conditions than in the Easy Difficulty conditions. Participant responses for sureness of direction judgments was consistent with the effect produced by VM. They were more sure when they had High VM and also performed significantly better in these conditions. Cognitive map performance was significantly correlated with direction judgments in both the Easy and Hard Difficulty conditions. As the map scores increased, error in direction judgment decreased. This is precisely what would be expected since increased map scores and decreases in direction judgment error both indicate a greater degree of spatial awareness.

Room reconstruct error. Researchers have used recreating the layout of objects memorized in a 3D room as a useful measure of cognitive map development. Traditionally, the reconstruction task is done on a 2D, scaled down floor-space representation. This experiment used the 3D perspective view and a 2D, scaled down view for memorizing—only the High VM groups had the 2D view for memorizing—and reconstructing the layout of a virtual room. One of the advantages of VEs for this kind of research is that

it easily allows the manipulation of the "world" which may not be possible in real environments.

Error for replacing pieces of furniture in their original positions was affected by the FOV afforded in the VE. Although the number of items correctly placed was greatest in the 90° FOV, only the 30° FOV placed significantly fewer objects than the 60° FOV and 90° FOV conditions. This result supports the notion that restricted FOVs place greater demands on memory and attention for integrating spatial information in the VE and impairs peoples' ability to develop an accurate cognitive representation of their surroundings. These results show that spatial reconstruction of the environment is sensitive to FOV restriction.

The findings for the reconstruction task in this experiment indicate that a 60° FOV or larger produced the best performance for spatial representation and orientation. It is possible that performance would have continued to increase if larger FOVs were used. Based on the findings from the cognitive map scores and from the reconstruct task, it is recommended that a 90° FOV or larger be used to optimize spatial orientation performance. FOVs larger than 90°, if possible, are being recommended because there was room for improved performance in all the spatial representation and orientation tasks.

Time to reconstruct the room layout in the previous task was significantly faster for the Low VM groups than for the High VM groups. This finding reflects that the High VM groups performed better in the reconstruction task and therefore took longer because they were accessing additional information during the task. Also, although the High VM and Low VM groups both had the overview map during the reconstruction task,

only the High VM groups had it during the memorizing portion of the task. Therefore, during reconstruction, participants in the High VM conditions were using both the 3D view and the map view for recall and recognition of object placement. This resulted in additional mental processing by participants in the High VM conditions.

The recommendations given above for setting FOV in desktop VEs should be used in consideration with the particular application in which they are being applied and attention should be paid to the types of tasks that users will be required to perform. Also, how VM is implemented will depend on these same factors.

Future Research

VEs are just beginning to enter the horizon of human-computer interaction. A more complete understanding of the perceptual, cognitive, and motor capabilities of humans in VEs needs to be investigated. Researchers have their tasks cut out for them if this tool is going to change the way in which humans interact with computers.

With the increased use of 3D graphics and the increasing processing speeds of personal computers, the impact of manipulating GFOV will be important for interaction with perspective displays. A more comprehensive model of the size and distance misperceptions as the result of GFOV changes is necessary. Several explanations have been offered thus far but do not completely explain the phenomenon. For example, researchers have attributed misperception of space in perspective presentations to truncation of the foreground, lack of binocular parallax, perceptions based on retinal image size rather than actual size, virtual space effect, and object-center cues

conflicting with world-centered cues. Additional research is needed to understand which of these explanations predict performance under egocentric and exocentric frames-of-reference on constructed 3D representations.

A large body of literature exists on how humans represent and interact with their surroundings. However, VEs impose a whole set of new challenges for understanding how these same capabilities are affected by computer-simulated worlds. The findings that have been collected from the real-world and VEs clearly show that FOV restriction in VEs is more detrimental. Researchers need to more fully define the situations in VEs under which performance losses due to FOV restriction occur.

Further research also needs to examine how distance distortions in cognitive maps manifest themselves in VEs, and the differences between cognitive distances based on exposure to VEs needs to be contrasted with real-world distance estimation. In this study it was shown that participants were unable to fully integrate information from the exocentric and egocentric viewpoints for spatial representation relating to distances. Researchers need to determine the interface design principles that afford users the most efficient information assimilation based on VM techniques.

Furthermore, how VEs can be symbolically enhanced has possibly the greatest potential for improving humans' interaction with simulated environments. This study has shown that VM can be used to overcome many of the problems associated with FOV restriction and task difficulty. VM is a concept that has received little empirical support. Researchers need to validate the use of VM on environments that are already 3D in nature to

further understand the implications of spatially representing information that is inherently spatial.

Lastly, the application of VM used in this VE study suggests that the model of VM outlined by Woods (1984) is in need of revision. Currently, the model characterizes VM to be on a continuum from low to high with spatial representation and spatial cognition at the high end, and the long shot toward the low end. The model implies that the VM techniques are on an ordinal scale. What the model does not account for is environments or applications that are inherently spatial. For example, the model could be interpreted to predict that because VEs have very high spatial representation, which is higher on the VM continuum than the long shot, the long shot would not benefit performance in this study. This study has shown that VM techniques are most certainly application specific, and it is unlikely that they can be characterized from low to high on an ordinal scale. The individual benefits of each VM design technique, under defined conditions, needs to be determine to fully explain why VM is such a powerful application design principle.

Conclusions

The purpose of this research was to evaluate the perceptual and cognitive capabilities of people in desktop VEs. These capabilities were evaluated under conditions that are known to cause perceptual errors in perspective displays because of limitations in humans' ability to accurately reconstruct the original 3D relationships presented via perspective on computer display screens. Specifically, manipulations in GFOV are known to cause not only perceptual errors but cognitive errors as well. The task

dependency of performance in truncated FOVs was also examined. This study addressed the questions few researchers have asked: How does the manipulation of GFOV affect egocentric perceptual judgments made from within the VE, based on information provided in egocentric and exocentric frames-of-reference? In addition, how does restricted FOV, or technically GFOV, affect spatial representation in desktop VEs?

Central to these questions was the manipulation of symbolic enhancements, in this case VM, to compensate for perceptual and cognitive processing restrictions placed on participants by the inherent nature of perspective displays and desktop VEs. VM was used to off-load some of the information processing demands caused by restricted FOVs. Moving these processing demands to the perceptual domain reduces the cognitive problem-solving requirements imposed by poor conception of the spatial relationships in VEs. An exocentric world view (long shot) and perceptual landmarks were used that had summary information providing a constant world model.

It has been shown that the basic characteristics of architectural space are not always accurately perceived in perspective displays. This has important implications for those who plan to use desktop VEs as a tool to represent spatial relations. Caution should be used when judgments of size and distance are important. Changes in GFOV resulted in distortions that manifested as a telephoto effect causing a compressed depth misperception. A 60° GFOV was found to be the optimum setting for perceiving architectural space dimensions in the perspective display. However, distance estimates to unseen targets were greatly overestimated.

Explanations of GFOV setting are inadequate to account for these results. Additional research needs to determine why people perceive their immediate spatial relationships in the VE one way and the global context of the VE in another.

Spatial representation and orientation in the VE was shown to be significantly affected by FOV. As the FOV became more restrictive, participants were less able to develop an accurate mental representation of the VE. The orientation of objects in these spaces were also misjudged. Performance decrements as the result of restricted FOV were also shown to be dependent on task difficulty. Increased task difficulty appears to place additional demands on memory and attentional resources which are already taxed because of restricted FOVs. The widest FOV, 90°, was the best at facilitating the development of cognitive maps in participants. It is assumed that even wider FOVs would continue to improve performance.

Spatial orientation in humans is considered to be associated with not only the ability to determine one's sense of direction, but the ability to incorporate spatial information from the environment into a cognitive map, providing an overall "picture" of the world. Even though both these attributes are considered to be two facets of the same construct, they may independently affect performance in different ways. For example, the cognitive map task and room reconstruct task were both intended to represent topological relations, which provide the relationships between locations or points in space. Topological relations are the information provided in a cognitive map. Metrical relations provide the information about the distance and direction between points, which was measured in this

experiment with the direction judgments and distance estimates to unseen targets. Overall, participants in this study performed much better with the topological relations than the metrical relations. Participants were able to reconstruct the room layout and draw mental maps; however, they had great difficulty with pointing and estimating distances to unseen targets. These are attributes expected to underlie navigation behavior in humans. It is evident that the participants are not developing a complete spatial representation of the VE. Designers of desktop VEs should be wary of the ability of users to navigate in these interfaces due to the limitations in the richness of spatial information. For example, users are having to interpret scale, visual information is reduced, and kinesthetic feedback is all but absent.

There appears to be a tradeoff between where to set GFOV in perspective displays depending on users needs. The wider the FOV in VEs, the more spatially oriented users will be while interacting with the interface. However, as the GFOV moves away from 60°, perceptual biases in size and distance occur. One method to maximize the tradeoffs between the two competing needs is to include symbolic enhancements in the interface.

VM in virtual worlds applied through use of the long shot and salient landmarks can significantly reduce problem-solving behavior by eliminating memory bottlenecks, attentional deficits, and poor formulation of the spatial representation. Elimination of these problems was particularly evident when task difficulty was increased. VM facilitates the extraction and integration of information across successive actions and views in the VE. Direction judgments, room dimension estimates, distance estimates, and the ability to

accurately develop a cognitive map of the environment were all improved by affording VM in the interface. However, in some cases VM was harmful to participants perception. For example, VM caused participants to increase their distance judgments to unseen targets, which were considerable greater than actual distances. The VM techniques applied in this study are founded on a spatial framework and capitalize on the spatial reasoning skills of humans.

This application of VM introduces additional spatial representation on environments that are inherently spatial. Sholl (1987) has shown that depending on how spatial information is learned, different types of information acquired are represented differently in people and can affect performance in orientation tasks. Specifically, primary knowledge is acquired through the environment directly, and secondary knowledge is indirectly acquired through sources, such as maps or other representations of the environment. Learning the representation of VEs through VM, which is secondary knowledge, profoundly impacted users' models in satisfactory and unsatisfactory ways.

Individual differences in spatial ability were shown to influence performance in the VE. Interestingly though, with the exception of time to reconstruct the room layout, spatial ability was not predictive of spatial orientation behavior. Measures that significantly correlated with spatial ability were more associated with space dimension estimates. Designers of desktop VEs need to be aware that if the application is intended to be used by people with average or below average spatial ability there may be

limitations as to how well they perceive, form representations of, and perform with VEs.

Although the Cube Comparisons test is intended to measure the ability of a person to remain oriented in relation to objects in space, it is possible that desktop VEs are not tapping this skill entirely. Other measures of spatial ability may be more appropriate for performance in VEs that lack the rich visual, auditory, and kinesthetic feedback.

Developers of desktop VEs need to consider the factors addressed in this research. Task difficulty and FOV can profoundly impact users' performance in VEs. If careful consideration is not given to these issues in VEs, users may misperceive the basic characteristics of space and have problems maintaining spatial orientation and representation, which will undoubtedly reduce navigation abilities. However, VE symbolic enhancements, such as VM can significantly improve the person-machine interface of VEs.

REFERENCES

- Alfano, P. L., and Michel, G. F. (1990). Restricting the field of view: Perceptual and performance effects. Perceptual and Motor Skills, 70, 35-40.
- Allen, G.L., Kirasic, K.K., Siegel, A.W., and Herman, J.F. (1979). Development issues in cognitive mapping: The selection and utilization of environmental landmarks. Child Development, 50, 1062-1070.
- Allen, G. L., Siegel, A. W., and Rosinski, R. R. (1978). The role of perceptual context in structuring spatial knowledge. Journal of Experimental Psychology: Human Learning and Memory, 4(6), 617-630.
- Aretz, A. J. (1991). The design of electronic map displays. Human Factors, 33(1), 85-101.
- Antin, J. F., Dingus, T. A., Hulse, M. C., and Wierwille, W. W. (1988). In F. Aghazadeh (Ed.), Trends in Ergonomics/Human Factors V. North-Holland: Elsevier Science.
- Arthur, E.J., Hancock, P.A., and Chrysler, S.T. (1993). Spatial orientation in real and virtual worlds. In Proceedings of The Human Factors and Ergonomics Society 37th Annual Meeting (pp. 328-332). Santa Monica, CA: Human Factors and Ergonomics Society.
- Bakeman, R. E., and Gottman, J. M. (1989). Observing interaction: An introduction to sequential analysis. Cambridge, England: Cambridge University Press.
- Barfield, W., Lim, R., and Rosenberg, C. (1990). Visual enhancements and geometric field of view as factors in the design of a three-dimensional perspective display. In Proceedings of the Human Factors Society 34th Annual Meeting (pp. 1470-1473). Santa Monica, CA: Human Factors Society.
- Bemis, S. V., Leeds, J. L., and Winer, E. A. (1988). Operator performance as a function of type of display: Conventional versus perspective. Human Factors, 30(2), 163-169.
- Billingsley, P. A. (1982). Navigation through hierarchical menu structures: Does it help to have a map? In: Proceedings of The Human Factors Society 26th Annual Meeting (pp. 103-107). Santa Monica, CA: Human Factors Society.
- Blades, M. (1990). The reliability of data collected from sketch maps. Journal of Environmental Psychology, 10, 327-339.
- Boff, K. R. and Lincoln, J. E. (Eds.). (1988). Engineering data compendium. Human perception and performance. AAMRL, Wright-Patterson AFB OH.

- Bordens, K. S. and Abbott, B. B. (1991). *Research design and methods: A process approach* (2nd edition). Mayfield Publishing: Mountain View, CA.
- Brickner, M. S. and Foyle, D. C. (1990). Field of view effects on a simulated flight task with head-down and head-up sensor imagery displays. In Proceedings of the Human Factors Society 34th Annual Meeting (pp. 1567-1571). Santa Monica, CA: Human Factors Society.
- Brown, M. H., Meehan, J. R., and Sarkar, M. (1993). Browsing graphs using a fisheye view. In Proceedings of INTERCHI '93 (pp. 516). New York, NY: Association for Computing Machinery.
- Byrne, R. W. (1979). Memory for Urban Geography. Quarterly Journal of Experimental Psychology, 31(1), 145-154.
- Canter, D. (1977). The psychology of place, The architectural Press, London.
- Couclelis, H., Golledge, R.G., Gale, N., and Tobler, W. (1987). Exploring the anchor-point hypothesis of spatial cognition. Journal of Environmental Psychology, 7, 99-122.
- Cornell, E. H. and Hay, D. H. (1984). Children's acquisition of a route via different media. Environmental and Behavior, 16, 627-641.
- Craik, K. H. (1976). Methods in environmental research. In H. M. Proshansky, W. H. Ittelson, and L. G. Rivlin (Eds.), Environmental Psychology: People and Their Physical Setting. New York, NY: Holt, Rinehart and Winston, Inc.
- De Jonge, D. (1962). Images of urban areas: Their structures and psychological foundations. Journal of the American Institute of Planners, 28, 266-276.
- Deregowski, J. B. (1972). Pictorial perception and culture. Scientific America, 227(5), 82-88.
- Dolezal, H. (1982). Living in a world transformed: Perceptual and performatory adaptation to visual distortion. New York, NY: Academic Press, Inc.
- Dorigi, N. S., Ellis, S. R., and Grunwald, A. J. (1993). Perspective format for a primary flight display (ADI) and its effect on pilot spatial awareness. In Proceedings of the Human Factors Society 37th Annual Meeting (pp. 1-5). Santa Monica, CA: Human Factors Society.
- Dvorine, I. (1953). The Pseudo-Isochromatic Plates, Second Edition. The Psychological Corporation.
- Ekstrom, R. B., French, J. W., and Harmon, H. H. (1976). Manual for kit of factor-referenced cognitive tests. Princeton: ETS.

- Ellis, S. R. (1991). Nature and origins of virtual environments: A bibliographical essay. Computing Systems in Engineering, 2(4), 321-347.
- Ellis, S. R. (1993). Pictorial communication: Pictures and the synthetic universe. In S. R. Ellis (Ed.), Pictorial Communication in Virtual and Real Environments (pp. 22-40). London: Taylor & Francis.
- Ellis, S. R. and Hacisalihzade, S. S. (1990). Symbolic enhancement of perspective displays. In Proceedings of the Human Factors Society 34th Annual Meeting (pp. 1465-1469). Santa Monica, CA: Human Factors Society.
- Ellis, S. R., and McGreevy, M. W. (1983). Influence of a perspective cockpit traffic display format on pilot avoidance maneuvers. In Proceedings of the Human Factors Society 27th Annual Meeting (pp. 762-766). Santa Monica, CA: Human Factors Society.
- Ellis, S. R., McGreevy, M. W., and Hitchcock, R. J. (1987). Perspective traffic display format and airline pilot traffic avoidance. Human Factors, 29, 371-382.
- Ellis, S. R., Smith, S., and Hacisalihzade, S. (1989). Visual direction as a metric of visual space. In Proceedings of the Human Factors Society 33rd Annual Meeting (pp. 1392-1395). Santa Monica, CA: Human Factors Society.
- Ellis, S. R., Tharp, G. K., Smith, S., and Grunwald, A. J. (1991). Exocentric judgments in real environments and stereoscopic displays. In Proceedings of the Human Factors Society 35th Annual Meeting (pp. 1442-1446). Santa Monica, CA: Human Factors Society.
- Evans, G. W. (1980). Environmental cognition. Psychological Bulletin, 88, 259-287.
- Evans, G. W., Marrero, D. G., and Butler, P. A. (1981). Environmental learning and cognitive mapping. Environment and Behavior, 13(1), 88-104.
- Gibson, E. J. (1969). Principles of perceptual learning and development. New York: Appleton-Century-Grofts.
- Golledge, R. G. (1978). Learning about urban environments. In T. Carlstein, D. Parkes and N. Thrift (Eds.), Timing space and spacing time (pp. 76-98). London: Edward Arnold.
- Gopal, S., Klatzky, R., and Smith, T. (1989). Navigator: a psychologically based model of environmental learning through navigation. Journal of Environmental Psychology, 9, 309-331.

- Gordon, A. D., Jupp, P. E., and Byrne, R. W. (1989). The construction and assessment of mental maps. British Journal of Mathematical and Statistical Psychology, *42*, 169-182.
- Grunwald, A. J. and Ellis, S. R. (1986). Spatial orientation by familiarity cues. In J. Patrick and K. D. Duncan, (Eds.), Training, human decision making and control (pp. 257-279). North-Holland: Elsevier.
- Grunwald, A. J., Ellis, S. R., and Smith, S. (1988). A mathematical model for spatial orientation from pictorial perspective displays. IEEE Transactions on Systems, Man, and Cybernetics, *18*(3), 425-431.
- Hagen, M. A., Jones, R. K., and Reed, E. S. (1978). On a neglected variable in theories of pictorial perception: Truncation of the visual field. Perception and Psychophysics, *23*(4), 326-330.
- Harrington, D. O. (1964). The visual field. St. Louis, MO: Mosby.
- Hartley, A. A. (1977). Mental measurement in the magnitude estimation of length. Journal of Experimental Psychology: Human Perception and Performance, *3*(4), 622-628.
- Henry, D. and Furness, T. (1993). Spatial perception in virtual environments: Evaluating an architectural application. In Proceedings of IEEE 1993 Virtual Reality Annual International Symposium, (pp. 33-40). Piscataway, NJ: IEEE Service Center.
- Herman, J. F. and Siegel, A. W. (1978). The Development of cognitive mapping of the large-scale environment. Journal of experimental Child Psychology, *26*, 389-406.
- Hix, D., and Hartson, H. R. (1993). Developing user interfaces: Ensuring usability through product and process. New York, NY: John Wiley & Sons, Inc.
- Hochberg, J. and Brooks, V. (1978). Film cutting and visual momentum. In J. W. Senders, D. F. Fisher, and R. A. Monty (Eds.), Eye Movements and the Higher Psychological Functions (pp. 293-313). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Hutchins, E. L., Hollan, J. D., and Norman, D. A. (1985). Direct manipulation interfaces. Human-Computer Interaction, *1*(4), 311-338.
- Isdale, J. (1993). What is virtual reality? A homebrew introduction and information resource list. (Online). Available FTP (or Telnet): [sune.uwaterloo.ca](ftp://sune.uwaterloo.ca) Directory: [pub/vr/documents](ftp://sune.uwaterloo.ca/pub/vr/documents) File: [whatisvr.txt](ftp://sune.uwaterloo.ca/pub/vr/documents/whatisvr.txt).
- Kasmar, J. V. (1970). The development of a usable lexicon of environmental descriptors. Environment and Behavior, *2*, 153-169.

- Keppel, G. (1991). Design and analysis: A researcher's handbook (Third Edition). Englewood Cliffs, New Jersey: Prentice Hall.
- Kim, W. S., Ellis, S. R., Tyler, M. E., Hannaford, B., and Stark, L. W. (1987). Quantitative evaluation of perspective and stereoscopic displays in three-axis manual tracking tasks. IEEE Transactions on Systems, Man, and Cybernetics, 17(1), 61-72.
- Kosslyn, S. M., Pick, H. L. Jr., and Fariello, G. R. (1974). Cognitive maps in children and men. Child Development, 45, 707-716.
- Kuipers, B. (1983). The cognitive map: Could it have been any other way? In H. L. Pick and L. P. Acredolo (Eds.), Spatial orientation: Theory, research and application. (pp. 345-359). New York: Plenum
- Levine, M. (1982). You-are-here maps: Psychological considerations. Environment and Behavior, 14, 221-237.
- Levine, M., Jankovic, I., and Palij, M. (1982). Principles of spatial problem solving. Journal of Experimental Psychology: General, 111, 157-175.
- Lindberg, E., and Garling, T. (1981). Acquisition of locational information about reference points during blindfolded and sighted locomotion: Effects of a concurrent task and locomotion paths. Scandinavian Journal of Psychology, 22, 101-108.
- Lynch, K. (1960). The image of the city. Cambridge, MA: MIT Press.
- Mainardi Peron, E., Baroni, M. R., Job, R., and Salmaso, P. (1990). Effects of familiarity in recalling interiors and external places. Journal of Environmental Psychology, 10, 255-271.
- McGreevy, M. W., and Ellis, S. R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. Human Factors, 28(4), 439-456.
- McGreevy, M. W., and Ellis, S. R. (1991). Format and basic geometry of a perspective display of air traffic for the cockpit. NASA Technical Memorandum 86680, Ames Research Center: Moffett Field, California.
- Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63, 81-97.
- Norman, D. A. (1988). The design of everyday things. New York, NY: Doubleday.
- Okabe, A., Oaki, K., and Hamamoto, W. (1986). Distance and direction judgment in a large-scale natural environment: The effects of a winding trail. Environment and Behavior, 18(6), 755-772.
- O'Neill, M. J. (1991). Evaluation of a conceptual model of architectural legibility. Environment and Behavior, 23(3), 259-284.

- O'Neill, M. J. (1992). Effects of familiarity and plan complexity on wayfinding in simulated buildings. Journal of Environmental Psychology, 12, 319-327.
- Osgood, R. K. and Wells, M. J. (1991) The effect of field-of-view size on performance of a simulated air-to-ground night attack. In Proceedings of Helmet Mounted Displays and Night Vision Goggles, (pp. 10-1-10-7). Pensacola, FL.
- Passini, R. (1984). Spatial representations, a wayfinding perspective. Journal of Environmental Psychology, 4, 153-164.
- Passini, R. (1992). Wayfinding in architecture. New York, NY: Van Nostrand Company Inc.
- Pearson, J. L., and Ialongo, N. S. (1986). The relationship between spatial ability and environmental knowledge. Journal of Environmental Psychology, 6, 299-304.
- Perrone, J. A. (1982). Visual slant underestimation: A general model. Perception, 11, 641-654.
- Pezdek, K. and Evens, G. W. (1979). Visual and verbal memory for objects and their spatial location. Journal of Experimental Psychology: Human Learning and Memory, 5(4), 360-373.
- Presson, C. C., and Hazelrigg, M. D. (1984). Building spatial representations through primary and secondary learning. Journal of Experimental Psychology: Learning, Memory, and Cognition, 10, 716-722.
- Rheingold, H. (1990). What's the big deal about cyberspace. In B. Laurel (Ed.), The Art of Human-Computer Interface Design (pp. 423-438). Reading, MA: Addison-Wesley Publishing Company, Inc.
- Roscoe, S. N. (1984). Judgment of size and distance with imaging displays. Human Factors, 26(6), 617-629.
- Rovine, M. J., and Weisman, G. D. (1989). Sketch-map variables as predictors of wayfinding performance. Journal of Environmental Psychology, 9, 217-232.
- Sedgwick, H. A. (1986). Space perception. In K. Boff, L. Kaufman, and J. Thomas (Eds), Handbook of Perception and Human Performance (pp. ??-??). New York: Wiley.
- Shneiderman, B. (1993). Designing the user interface: Strategies for effective human-computer interaction. Reading, MA: Addison-Wesley.
- Sholl, M. J. (1987). Cognitive maps as orienting schemata. Journal of Experimental Psychology: Learning, Memory, and Cognition, 13(4), 615-628.

- Smith, T. R., Pellegrino, J., and Golledge R. G. (1980). Computational process modeling of spatial cognition and behavior. Geographical Analysis, 14, 305-325.
- Tharp, G. K., Ellis, S. R. (1990). The effects of training on errors of perceived direction in perspective displays. NASA Technical Memorandum 102792. Ames Research Center, Moffett Field, CA.
- Thomas, J. C. (1992). Human factors issues in virtual reality. In T. Middleton (Ed.), Proceedings of virtual worlds: Real challenges - Papers from SRI's 1991 conference on virtual reality (pp. 1-4). Westport, CT: Meckler Publishing.
- Tolman, E. C. (1948). Cognitive maps in rats and men. Psychological Review, 55(4) 189-208.
- Venturino, M. and Kunze, R. J. (1989). Spatial awareness with a helmet-mounted display. In Proceedings of the Human Factors Society 33rd Annual Meeting (pp. 1388-1391). Santa Monica, CA: Human Factors Society.
- Venturino, M. and Wells, M. J. (1990). Head movements as a function of field-of-view size on a helmet-mounted display. In Proceedings of the Human Factors Society 34th Annual Meeting (pp. 1572-1576). Santa Monica, CA: Human Factors Society.
- Vincente, K. J. and Williges, R. C. (1988). Accommodating individual differences in searching a hierarchical file system. International Journal of Man-Machine Studies 29, 647-668.
- Weisman, G. D., O'Neill, M. J., and Doll, C. (1987). Computer graphic simulation of wayfinding in a public environment: a validation study. In J. Harvey and D. Henning (Eds.), Environmental Design Research Association Proceedings, 18, 74-80.
- Wells, M. J. (1992). Virtual reality: Technology, experience, assumptions. Human Factors Society Bulletin, 35(9), 1-3.
- Wells, M. J. and Venturino, M. (1989). The effect of increasing task complexity on the field-of-view requirements for a visually coupled system. In Proceedings of the Human Factors Society 33rd Annual Meeting (pp. 91-95). Santa Monica, CA: Human Factors Society.
- Wells, M. J. and Venturino, M. (1990). Performance and head movements using a helmet-mounted display with different sized fields-of-view. Optical Engineering, 29(8), 870-877.
- Wells, M. J., Venturino, M., and Osgood, R.K. (1988). Using target replacement performance to measure spatial awareness in a helmet-mounted simulator. In

- Proceedings of the Human Factors Society 32nd Annual Meeting (pp. 1429-1433). Santa Monica, CA: Human Factors Society.
- Wells, M. J., Venturino, M., and Osgood, R. K. (1989). The effect of field-of-view size on performance at a simple simulated air-to-air mission. In Helmet-Mounted Displays: Proceedings of the SPIE Conference (pp. 126-137). Bellingham, WA: International Society for Optical Engineering.
- Wickens, C. D. (1992a). Engineering psychology and human performance. New York, NY: Harper Collins Publishers.
- Wickens, C. D. (1992b). Virtual reality and education. In Proceedings of the 1992 IEEE International Conference on Systems, Man, and Cybernetics (pp.842-847). New York, NY: Institute of Electrical and Electronics Engineers.
- Wickens, C. D., and Baker, P. (In press). Cognitive issues in virtual reality. In W. Barfield and T. Furness (Eds.), Advanced interface design and virtual environments. Oxford University Press.
- Wickens, C. D. and Todd, S. (1990). Three dimensional display technology for aerospace and visualization. In Proceedings of the Human Factors Society 34rd Annual Meeting (pp. 1567-1571). Santa Monica, CA: Human Factors Society.
- Wilcox, R. L., and Teghtsoonian, M. (1971). The control of relative size by pictorial depth cues in children and adults. Journal of Experimental Child Psychology, 11, 413-429.
- Wise, J. A., and Debons, A. (1987). Principles of film editing and display system design. In Proceedings of the Human Factors Society 31st Annual Meeting (pp. 121-124). Santa Monica, CA: Human Factors Society.
- Woods, D. D. (1984). Visual momentum: A concept to improve the cognitive coupling of person and computer. International Journal of Man-Machine Studies, 21, 229-244.

APPENDIX A

Post-test Questionnaire

APPENDIX B

Introduction to the Study

Introduction to the Study

The purpose of this study is to investigate the relationship between human spatial cognition and the design of "desktop" virtual environments. The study is being conducted in the Human Computer Interaction Laboratory (HCIL), Department of Industrial and Systems Engineering (ISE) at Virginia Tech. It is being conducted under the Interactive Accessibility project sponsored by the National Science Foundation. The principal investigators are Dennis C. Neale, a graduate student in ISE, and Dr. R. C. Williges, director of the HCIL.

In this study you will be asked to perform various orientation and navigation tasks in a desktop virtual environment. The design of the computer interface is being evaluated, not you. Please do not feel nervous about performing any of the tasks, just follow the instructions and proceed in a comfortable manner.

You will be asked to come into the HCIL and spend approximately 1 1/2 hours in the experiment. After reading this introduction to the study, you will be asked to fill out an informed consent form. If you agree to participate, your vision will be tested to insure that you have at least 20/40 corrected vision and are able to distinguish colors. If you meet the vision requirements, you will be given a simple paper and pencil test to determine your spatial orientation abilities.

Before performing any tasks in the virtual environments, you will be given the opportunity to view instruction videos demonstrating how to use the computer application. A standard amount of time will then be given to practice interacting with the virtual environment application.

Once you have practice and are proficient at moving around in a virtual world, you will be asked to perform several types of orientation tasks while navigating through a simulated office building.

Following the tour of the office building, you will be asked to fill out a subjective questionnaire regarding your impression of the virtual environments. If you pass the vision requirements and participate in the study, you will be paid \$5 per hour. During the experiment, if for any reason you decide not to continue, you will be compensated only for the time in which you actually participated. Also, occasionally equipment failures do occur. If this is the case, you will similarly only be paid for the time actually spent in the experiment.

If you are still interested in participating in the study, please read and sign the informed consent form. Thank you for your participation.

APPENDIX C

Participant's Informed Consent

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

Title of Project: Interactive Accessibility project

Principal Investigator: Dennis C. Neale

I. THE PURPOSE OF THIS RESEARCH AND ITS PROCEDURES

- You are invited to participate in this study whose purpose, description, and procedures are contained in the Introduction to the Study document, which you have already read. This study will have a total of 60 participants. There are minimal risks to you in this study.

II. BENEFITS OF THIS PROJECT

- In addition to payment, you may learn something from the experiment and find it interesting.
- No guarantee of benefits has been made to encourage you to participate.
- You may receive a synopsis or summary of this research when completed. If you are interested, please write down your mailing address on the following page.

III. EXTENT OF ANONYMITY AND CONFIDENTIALITY

- The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than individuals working on the project without your written consent. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

IV. COMPENSATION

- For participation in the project you will receive \$5 per hour. Payment will be made following the completion of your participation.

V. FREEDOM TO WITHDRAW

- You are free to withdraw from this study at any time without penalty. If you chose to withdraw, you will be compensated for the portion of the time of the study.

If the investigator terminates the experiment because of equipment failure, you will be compensated for the portion of the project completed.

VI. APPROVAL OF RESEARCH

- This research project has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University.

VII. SUBJECT'S RESPONSIBILITIES AND PERMISSION

- I know of no reason I cannot participate in this study.
- I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.
- If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Signature _____

Date _____

VIII. SUBJECT'S CONTACTS

Should I have any question about this research or its conduct, I will contact:

<hr/> Dennis C. Neale Investigator	<hr/> 1x9089 Phone
<hr/> Dr. R. C. Williges Faculty Advisor	<hr/> 1x6270 Phone
<hr/> Ernest R. Stout Chair, IRB Research Division	<hr/> 1x9359 Phone

APPENDIX D

General Instructions

General Instructions (Phase I)

1. You will be asked to estimate room dimensions while in the virtual environment. Do not use the furniture or any other heuristic method to try and measure or count off the dimensions of the space. Please just estimate the dimensions from your general impression of the room size.
2. You can progress at your own pace and look around as much as you would like while moving through the virtual environment; however, please do not deviate from the path that you will be instructed to follow as you continue through the virtual environment.
3. While moving through the virtual environment, please try to understand and remember the layout of the space because you will be asked to recreate the floor plan of the office building at the end of your tour. Also, please remember the location of the building entrance because you will be asked to point to it throughout your tour.
 - Statement 4 in the general instructions will only be given to participants in the visual momentum conditions.
4. Be sure to use the overview map while performing tasks in the virtual environment.

General Instructions (Phase II)

1. You will be given one minute to memorize the location of several objects in a room similar to the one you just practiced in. You can navigate freely or use any viewpoint in the time allotted.
2. Following this task, the objects will be removed and placed outside the room. You will be required to replace the objects in their original positions. Please focus on remembering the positions of objects because the objects themselves will be available to you during the room reconstruction task.
3. Time and accuracy are equally important. Work as fast and accurately as you can.
 - Statement 4 and 5 in the general instructions will only be given to participants in the visual momentum conditions.
4. The overview map will be available to you throughout the room reconstruction. Remember that you can use the overview map when trying to memorize the location of objects in the room.
5. The colored objects will not be removed for the reconstruction task. They will remain in their original position. You can use these to help you remember the location of other objects.

APPENDIX E
Verbal Instructions

Transcript of Verbal Instructions for Phase 1 of the Experiment

1. Remember the location of the entrance and the general layout of the space.
2. Proceed into the building.
3. [They are then given instructions for proceeding to each of the rooms in the building (e.g. Go to the end of the hall and turn left.)]
4. Go to the center of the room indicated by the dot on the floor.
5. Face in the direction of the:
 - object from the previous room by centering the cross hairs directly at the object.
Estimate the distance to the object.
 - entrance to the building by centering the cross hairs directly at the entrance.
Estimate the distance to the entrance

[The order in which they do the pointing tasks in 5 depends on the treatment order for the within-subjects factor (see Table 1.). Also, pointing tasks are performed in only 6 out of the 8 rooms (B through G).]
4. Move freely around the room until you feel comfortable that you can estimate the room dimensions. Pay particular attention to the (respective object in each room, i.e., folding chair) because you will be asked to point to the center of its location from the next room.
5. [They are then given instructions for exiting the building.]

APPENDIX F

Additional Results of Statistical Analysis

Table 1. Correlations and confidence intervals for the covariate and dependent measures.

	Correlation	Confidence Intervals	
		95% Lower	95% Upper
Spatial, Cognitive Map	*.259	5.918E-3	.482
Spatial, Dist. to Object	-.312	-.524	-.063
Spatial, Dist. to Entrance	-.264	-.485	-.011
Spatial, Degree to Object	*-.076	-.323	.182
Spatial, Degree to Entrance	*-.034	-.285	.222
Spatial, Room Sizes	-.372	-.572	-.131
Spatial, Object Error	*.254	-2.368E-4	.477
Spatial, Object Time	-.319	-.530	-.070

* Not significant at $p < 0.05$

Table 2. Mean and standard deviation summary for room size.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	495.567	571.552	104.351
Yes VM	30	651.333	636.063	116.129
30	20	368.200	309.019	69.099
60	20	694.800	710.854	158.952
90	20	657.350	683.527	152.841
NO VM, 30	10	268.200	176.587	55.842
NO VM, 60	10	814.100	904.675	286.083
NO VM, 90	10	404.400	153.556	48.559
Yes VM, 30	10	468.200	384.956	121.734
Yes VM, 60	10	575.500	465.519	147.210
Yes VM, 90	10	910.300	905.851	286.455

Table 3. LSD test on all pairwise comparisons for room size estimates.

		Versus	Diff	Crit. diff.		
						FOV
		90	289.2	285.74	S	
	60	90	37.5	285.74		
VM x FOV	No VM, 30	No VM, 60	545.9	404.05	S	
		No VM, 90	136.2	404.05		
		Yes VM, 30	200.0	404.05		
		No VM, 60	Yes VM, 60	238.6	404.05	
		No VM, 90	Yes VM, 90	505.9	404.05	S
		Yes VM, 30	Yes VM, 90	442.1	404.05	S
		Yes VM, 60	Yes VM, 90	442.1	404.05	S

S = Significantly different at the .05 level of significance.

Table 4. LSD test on all pairwise comparisons for distance judgments.

	Versus		Diff	Crit. diff.	
FOV	30	60	118.5	108.8	S
		90	193.2	108.8	S
	60	90	74.7	108.8	
Difficulty x VM	Easy, No VM	Hard, No VM	333.63	141.2	S
	Easy, Yes VM	Hard, Yes VM	87.66	141.2	
	Hard, No VM	Hard, Yes VM	207.2	141.2	S
Difficulty x FOV	Easy, 30	Hard, 30	103.45	153.9	
	Easy, 60	Hard, 60	240.6	153.9	S
	Easy, 90	Hard, 90	287.9	153.9	S
	Hard, 30	Hard, 60	187.05	153.9	S
		Hard, 90	285.4	153.9	S

S = Significantly different at the .05 level of significance.

Table 5. Means and standard deviation summary for distance estimates.

	Count	Mean	Std. Dev.	Std. Error
30	40	200.925	113.114	17.885
60	40	319.400	411.739	65.102
90	40	394.100	376.151	59.475
Easy	60	199.483	166.074	21.440
Hard	60	410.133	420.440	54.279
Easy, NO VM	30	180.100	135.797	24.793
Easy, Yes VM	30	218.867	192.077	35.068
Hard, NO VM	30	513.733	486.575	88.836
Hard, Yes VM	30	306.533	317.291	57.929
Easy, 30	20	149.200	74.185	16.588
Easy, 60	20	199.100	127.036	28.406
Easy, 90	20	250.150	242.155	54.147
Hard, 30	20	252.650	122.992	27.502
Hard, 60	20	439.700	548.977	122.755
Hard, 90	20	538.050	433.778	96.996

Table 6. Means and standard deviation summary for cognitive map scores.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	26.400	9.460	1.727
Yes VM	30	36.200	7.572	1.382
NO VM, 30	10	24.800	3.225	1.020
NO VM, 60	10	23.400	13.550	4.285
NO VM, 90	10	31.000	7.616	2.408
Yes VM, 30	10	38.100	7.992	2.527
Yes VM, 60	10	37.500	6.570	2.078
Yes VM, 90	10	33.000	7.775	2.459

Table 7. LSD test for cognitive map scores.

VM x FOV		Versus		Diff	Crit. diff.
	No VM, 30	No VM, 90		6.2	5.8 S
		Yes VM, 30		13.3	5.8 S
	No VM, 60	No VM, 90		7.6	5.8 S
		Yes VM, 60		14.1	5.8 S
	No VM, 90	Yes VM, 90		2	5.8

S = Significantly different at the .05 level of significance.

Table 8. Means and standard deviation summary table for direction judgments.

	Count	Mean	Std. Dev.	Std. Error
NO VM	60	41.197	29.326	3.786
Yes VM	60	4.972	2.121	.274
Easy, NO VM	30	33.423	27.011	4.931
Easy, Yes VM	30	4.627	2.000	.365
Hard, NO VM	30	48.972	29.918	5.462
Hard, Yes VM	30	5.317	2.216	.405
Easy, 30	20	15.874	16.200	3.623
Easy, 60	20	19.276	20.561	4.597
Easy, 90	20	21.925	32.707	7.313
Hard, 30	20	26.284	28.640	6.404
Hard, 60	20	29.283	33.233	7.431
Hard, 90	20	25.867	30.760	6.878

Table 9. LSD test for the direction judgment difficulty x VM interaction.

Difficulty x VM	Versus		Diff	Crit. diff.	
	Easy, No VM	Hard, No VM	15.55	8.24	
Easy, Yes VM	Hard, Yes VM	.69	8.24		

S = Significantly different at the .05 level of significance.

Table 10. Means summary table of object placement error.

	Count	Mean	Std. Dev.	Std. Error
30	20	.514	.227	.051
60	20	.677	.187	.042
90	20	.735	.235	.052

Table 11. LSD test for FOV object placement error.

FOV	Versus		Diff	Crit. diff.	
	30	60	.16	.13	
	90	.22	.13	S	

S = Significantly different at the .05 level of significance.

Table 12. Means summary table for room reconstruct time.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	4.922	1.790	.327
Yes VM	30	6.148	2.768	.505

Table 13. Means summary table for Question 1.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	3.700	1.236	.226
Yes VM	30	3.033	1.159	.212

Table 14. ANOVA summary table for Question 2.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	1.667	1.667	.760	.3871
FOV	2	1.033	.517	.236	.7909
VM * FOV	2	3.633	1.817	.829	.4422
Residual	54	118.400	2.193		

Dependent: Rating

Table 15. ANOVA summary table for Question 3.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	3.267	3.267	1.487	.2279
FOV	2	11.100	5.550	2.527	.0893
VM * FOV	2	3.433	1.717	.782	.4628
Residual	54	118.600	2.196		

Dependent: Rating

Table 16. ANOVA summary table for Question 4.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	.417	.417	.152	.6978
FOV	2	3.100	1.550	.567	.5707
VM * FOV	2	1.633	.817	.299	.7431
Residual	54	147.700	2.735		

Dependent: Rating

Table 17. ANOVA summary table for Question 5.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
VM	1	1.067	1.067	.372	.5444
FOV	2	1.300	.650	.227	.7979
VM * FOV	2	9.433	4.717	1.645	.2025
Residual	54	154.800	2.867		

Dependent: Rating

Table 18. Means summary table for Question 6.

	Count	Mean	Std. Dev.	Std. Error
30	20	4.900	1.294	.289
60	20	4.150	1.424	.319
90	20	5.450	1.395	.312
NO VM, 30	10	5.700	1.059	.335
NO VM, 60	10	4.700	1.494	.473
NO VM, 90	10	5.000	1.491	.471
Yes VM, 30	10	4.100	.994	.314
Yes VM, 60	10	3.600	1.174	.371
Yes VM, 90	10	5.900	1.197	.379

Table 19. All LSD tests for Question 6.

FOV	Versus		Diff	Crit. diff.	
	60	90			
VM x FOV	NO VM, 30	Yes VM, 30	1.6	1.13	S
	NO VM, 60	Yes VM, 60	1.1	1.13	S
	NO VM, 90	Yes VM, 90	.9	1.13	
	Yes VM, 30	Yes VM, 90	1.8	1.13	S
	Yes VM, 60	Yes VM, 90	2.3	1.13	S

Table 20. Mean summary for VM on Question 7.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	3.733	1.461	.267
Yes VM	30	2.000	1.174	.214

Table 21. Means summary table for VM on Question 8.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	4.900	1.768	.323
Yes VM	30	2.000	1.145	.209

Table 22. All means for Question 9.

	Count	Mean	Std. Dev.	Std. Error
NO VM	30	5.200	1.627	.297
Yes VM	30	4.300	1.512	.276
NO VM, 30	10	5.500	1.269	.401
NO VM, 60	10	5.600	1.647	.521
NO VM, 90	10	4.500	1.841	.582
Yes VM, 30	10	3.700	1.252	.396
Yes VM, 60	10	4.000	1.491	.471
Yes VM, 90	10	5.200	1.476	.467

Table 23. LSD test for the VM by FOV interaction on Question 9.

VM x FOV	Versus		Diff	Crit. diff.
	NO VM, 30	Yes VM, 30		
	NO VM, 60	Yes VM, 60	1.8	1.36 S
	NO VM, 90	Yes VM, 90	1.9	1.36 S
			.7	1.36

Table 24. Correlations and confidence intervals for dependent measures and questionnaire responses.

	Correlation	Confidence Intervals	
		95% Lower	95% Upper
Room size, Dist. to Object	.841	.746	.902
Room size, Dist. to Entrance	.767	.638	.855
Cognitive Map, Degrees to Object	-.434	-.619	-.202
Cognitive Map, Degrees to Entrance	-.591	-.735	.397
Room size, Question 6	.254*	1.504E-4	.477
Degrees to Object, Question 7	-.372	-.572	-.131
Degrees to Entrance, Question 8	.829	.728	.895
Cognitive Map, Question 9	-.619	-.755	-.434

* Not significant at $p < 0.05$

DENNIS C. NEALE

804 North Dr.
Blacksburg, Virginia 24060
(703) 951-7739

Industrial & Systems Engineering,
Virginia Polytechnic Institute & State
University, Blacksburg, VA 24060
(703)231-3193 email: dneale@vt.edu

EDUCATION

M.S., Industrial and Systems Engineering (Human Factors Option)
Virginia Polytechnic Institute and State University, Blacksburg, VA - May, 1995
THESIS: "Spatial Perception in Perspective Displays as a Function of Field-of-view and Virtual Environment Enhancements Based on Visual Momentum Techniques."

M.A., Applied Experimental Psychology/Human Factors
California State University, Northridge, Northridge, CA (ABT) - May, 1991

B.A., Cognitive Psychology
University of California, San Diego, San Diego, CA - December, 1988

WORK EXPERIENCE

Graduate Research Assistant (9/93 - present)
Virginia Polytechnic Institute & State University, Department of Industrial and Systems Engineering, Human-Computer Interaction Laboratory, Blacksburg, VA

- Funded under the National Science Foundation Institutional Infrastructure Award, Interactive Accessibility: Breaking Barriers to the Power of Computing.
- Conducted research on virtual reality systems
- Participated in designing a usability methods research laboratory
- Designed and developed the World Wide Web server html documents for the Human Factors Engineering Centers

Human Factors Specialist (2/93 - 6/93)
Virginia Polytechnic Institute & State University, Division of Business & Community Relations, Blacksburg, VA

- Designed and developed a computer system for business and industry to use in accessing university services and electronic databases
- Performed a needs analysis surveying business and industry throughout Virginia

Usability Testing Laboratory Director (7/91-7/92)
Xerox Corporation, El Segundo, CA

- Formulated and directed Xerox's customer documentation usability lab
- Conducted usability tests with printer hardware and software
- Conducted comparison studies - statistical analysis
- Designed documentation formats and graphics
- Created and conducted surveys
- Wrote design specification and validation reports
- Provided formal briefings to management and technical groups

Member of the Technical Staff (MTS) (6/91-11/91)
The Aerospace Corporation, Operator Interface Engineering, El Segundo, CA

- Developed a dynamic computer prototype of a multi-operator satellite mission control system
- Redesigned an in-house database's human-computer interface
- Designed, coded, and tested software for system functionality
- Reviewed and modified Operator Interface (OI) and Operational Sequence Diagrams (OSDs)

- Created computer interface design documents
- Interfaced with Air Force operational command to meet design specifications

Research Assistant (4/89-7/89)

Salk Institute for Biological Studies, Language/Cognition Lab, San Diego, CA

- Developed computer interfaces for brain damaged and mentally handicap populations
- Directed the development and maintenance of the cognition laboratory's computer database
- Conducted experiments and analyzed data
- Supervised and directed student interns
- Administered batteries of psychological tests to disabled and normal populations

TEACHING EXPERIENCE

Statistics Tutor (9/90-6/91)

California State University, Northridge, Northridge, CA

- Tutored individuals and groups for intermediate statistics course
- Covered descriptive and inferential statistics

Graduate Teaching Assistant (1/90-6/90)

California State University, Northridge, Northridge, CA

- Instructed a Sensation & Perception course
- Researched, created, and organized lectures and experiments
- Graded exams, homework, and APA style literature review papers

PUBLICATIONS & PRESENTATIONS

Neale, D. C., and Kies, J. K. (1995). User-generated scenarios for requirements specification and design rationale. Paper presented at the Human Computer Interaction Consortium, Fraiser: CO, (pp. 1-5).

Neale, D. C., Lewis, V.R., and Petitt, C. (1994). A systems approach for incorporating human factors in the development of a computer-based multimedia vacation planning system. Proceedings of the 2nd Annual Mid-Atlantic conference of the Human Factors and Ergonomics Society, (pp. 70-74).

Neale, D. C. (1993). "Partnership in progress: A program designed to provide a forum for the exchange of ideas, research and knowledge between the university and businesses, companies, and corporations." Seminar presented for the Business and Community Relations Department, Virginia Polytechnic Institute & State University, Blacksburg, VA

TECHNICAL REPORTS

Neale, D. C., Kelly, S., and Balderrama, J. (1992). Fortress customer documentation validation test report, (Tech. Report No. ESCP305-08). El Segundo: Xerox Corporation.

Neale, D. C., Balderrama, J., and Kelly, S. (1992). Fortress HP emulation validation test report, (Tech. Report No. ESCP305-07). El Segundo: Xerox Corporation.

Neale, D. C., and Balderrama, J. (1992). Sumida content review, (Tech. Report No. ESCP305-06). El Segundo: Xerox Corporation.

Neale, D. C., Balderrama, J., and Kelly, S. (1992). Lion validation test report, (Tech. Report No. ESCP305-05). El Segundo: Xerox Corporation.

Neale, D. C., Balderrama, J. (1992). Fortress validation test report, (Tech. Report No. ESCP305-04). El Segundo: Xerox Corporation.

Neale, D. C., Balderrama, J., and Kelly, S. (1992). Jupiter validation test report, (Tech. Report No. ESCP305-03). El Segundo: Xerox Corporation.

Neale, D. C., Balderrama, J. and Kelly, S. (1992). Soleil customer documentation validation results, (Tech. Report No. ESCP305-02). El Segundo: Xerox Corporation.

Neale, D. C., and Kelly, S. (1992). Sumida customer documentation validation results, (Tech. Report No. ESCP305-01). El Segundo: Xerox Corporation.

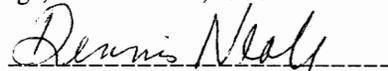
Neale, D. C. (1991). CSOC Calendar system user interface, (Tech. Report No. IOC 91-5822.5-51). El Segundo: The Aerospace Corporation, Operator Interface Engineering.

PROFESSIONAL AFFILIATIONS

- Association for Computing Machinery (ACM), 1991 - present
- Human Factors and Ergonomics Society (HFES), 1988 - present
- Special Interest Group on Computer & Human Interaction (ACM SIGCHI), 1991 - present
- Virginia Tech Student Chapter of the Human Factors and Ergonomics Society (HFES), 1992 - present

ACTIVITIES & HONORS

- Human Factors and Ergonomics Society (HFES) Conference Committee Member, 3rd Annual Mid-Atlantic Conference, Virginia Polytechnic Institute & State University, 1995
- Los Angeles Human Factors and Ergonomics Society (LAHFES) Student Liaison Representative, 1991
- Industrial and Systems Engineering Tuition Scholarship, Virginia Polytechnic Institute & State University, 1992 - 1993
- National Honor Society in Psychology , Life Member, 1989
- Dean's Honor List, California State University, Northridge, 1989 - 1991
- Academic Achievement Award, El Camino College, Torrance CA., 1986



Dennis C. Neale