

Experiments in the Use of Immersion for Information Visualization

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Thesis submitted to the faculty of
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Computer Science and Applications

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May 8th, 2002
Blacksburg, VA, USA

Keywords: Interaction Techniques, Overview + detail, Virtual
Environments, Human Factors

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Abstract

Information visualization (info vis) deals with how to increase the bandwidth of effective communication between computer and human, enabling us to see more, understand more, and accomplish more. Traditionally, it deals with interaction and display techniques of visualizing often abstract data on the two-dimensional desktop.

Immersive virtual environments (VEs) offer new, exciting possibilities for information visualization. Immersion gives an enhanced realistic effect, and can improve spatial understanding and orientation. By identifying or developing useful interaction techniques (ITs), we can develop VE systems for better information visualization.

This thesis has two different experiments that were related to two different sides of the study of use of immersion for VEs. One of the experiments is related to abstract data visualization in an immersive VE. The other one was motivated by the need for enhancing a realistic VE with additional data.

In our first experiment, our focus is on implementing overview+detail techniques in VEs. Our hypothesis is that VE-specific ITs should borrow from, but not copy existing 2D IT technique for overview +detail. We develop ITs for use in VEs and show that they are easy to use and useful using task-based usability evaluation. We develop the “jump” technique for use in this application, which can be generalized to numerous other applications. The tangible contribution of this research is Wizard, an application for infovis in VEs.

Our second hypothesis is that if the data to be visualized has inherent spatial attributes, it can be visualized well in immersive virtual environments. We investigate the trends using an experiment that tests people’s understanding of spatial attributes under immersive and desktop conditions. Although not statistically significant, we observed a moderate trend indicating that immersion decreases the time needed to perform a spatial information-gathering task. We believe that this area of research can be applied immediately to the applications currently being developed.

Acknowledgement

I, as you know me now, am a product of my inborn self, influenced in numerous ways by the bittersweet memories, more sweet than bitter.

There are some who I am infinitely grateful to. A hymn in Marathi says,

First, I bow to God; I pledge my life for your service.

Second, I bow to mother, Aai; there are no limits to your compassion and love.

Third, I bow to the motherland; for giving me a place to live and to prosper. I also thank the country that has given me immense knowledge and education. It is truly the land of opportunities.

Fourth, I bow to my father, Baba, thank you for all your support.

Fifth I bow to my teachers, who so lovingly taught me everything I know.

To my teachers, the wonderful people who guided me in this Masters thesis. Dr. North, who introduced me to the concept of information visualization, I had a great time in the infovis class. Dr. Kriz, for his support throughout a year and half I spent in this lab. Thanks for all those anecdotes that taught me so much about life. Dr. Buikema and Dr. Nance, my supervisors who made my jobs an enjoyable learning experience.

Dr. Bowman, the person who guided me, motivated me, and kept me going. Thanks for the support you gave when I needed it. Thank you for giving me the great opportunities that I had during my graduate studies. I cannot imagine what I put you through, especially in the last couple of months, me running like a mad hatter trying to wrap up the thesis. Words are inadequate in expressing my gratitude, all I can say is - Thanks for Everything.

Chad, thanks for introducing me to VEs. Prasuna, who helped me during various stages of the thesis, Laura who proof read this document, Xin, Fernando and Dr. Ollendick, who helped in the analysis and statistics – You are terrific people! I am grateful for all your help.

Thank you Aaji, Sanju, Nanna, Aditya, Makarand, for being the great people you are, its great to have a great family for support. To all my relatives, all of you are pillars to my success.

Thank you Pink Floyd, your music helped me work through the long hours of solitude while coding in the lab. To Bollos, the coffee shop downtown, that kept me awake in the wee hours of the morning.

To all the people who have made a difference in my life, and made me the person I am, thank you.

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Preface

“Is this the real life?
Is this just fantasy?
Caught in a land-side,
no escape from reality.”

- Bohemian Rhapsody, Queen

Escape from reality in the world of synthetic reality; is this just fantasy? Is that the real life? Are dreams virtual realities?

Why construct virtual environments? Why construct artificial life environments? Why do we feel the need to create something when we seem to have so little understanding of why the natural world exists?

Too many questions unanswered. Any takers?

1 Introduction

In this thesis, we present the development of interaction techniques that help information visualization in virtual environments. We also present a study of characteristics of dataset that make it more suited for visualization in a particular environment.

This chapter introduces some of the terms, mentions some factors that motivated our study, introduces the problem statement and then briefly outlines our approach.

1.1 What is Infovis?

Information visualization (infovis) is an upcoming area of research in the field of Human Computer Interaction (HCI) that deals with how to increase the bandwidth of effective communication between computer and human; enabling us to see more, learn more, understand more and accomplish more. In a simplistic way, it involves identifying representations and metaphors, and using interactivity to allow us to perceive more than what can be realized from static tables and datasets. It deals with the interaction and display techniques of visualizing often abstract data on the two-dimensional desktop screen.

1.2 What are Virtual Environments?

Kalawsky [Kalawsky93] explained that a Virtual Environment (VE), also known as virtual reality, is a computer system that generates a three-dimensional graphical ambient known as virtual world, where the user experiences an effect called immersion (the sense of presence within the VE world), and he/she navigates through the virtual world and interacts with the graphical objects that reside within it, using special input/output devices.

In terms of user interface, we can think of virtual environments as a human-computer interface in which the computer creates a sensory-immersing environment that interactively responds to and is controlled by the behavior of the user.

In this section, we introduce some of the terminology often used in VE literature.

1.2.1 Immersion

We call a computer system an immersive virtual environment since it immerses a representation of the person's body in a synthetic environment. The sensory data perceived by the user is computer-generated in an immersive virtual environment.

According to [Slater95] "Immersion includes the extent to which the computer displays are extensive, surrounding, inclusive, vivid and matching. They are surrounding to the extent that information can arrive at the person's sense organs from any (virtual) direction, and the extent to which the individual can turn towards any direction and yet remain in the environment."

Immersion is a quantifiable description of the technology that provides immersion. Thus a person wearing a head mounted display that has spatial audio is considered to be highly immersed in the VE.

1.2.2 Presence

Presence is the psychological sense of "being there" in the environment. It is an experience felt by the user. An Immersive VE may lead to a sense of presence for a participant taking part in such an experience.

Lombard [Lombard97] puts forth six conceptualizations of presence. For research in VEs, the specific conceptualization concerns the degree to which a medium can produce seemingly accurate representations of objects, events, and people -- representations that look, sound, and/or feel like the "real" thing. Another conceptual definition of presence involves the idea of transportation. [Lombard97] identifies three distinct types: "You are there," in which the user is transported to another world, "It is here," in which another world is transported to the user, and "We are together," in which two or more users are transported together to a common world that they can share.

1.2.3 Immersion versus presence

Immersion and presence, while often erroneously thought to be identical, are in fact orthogonal [Slater95]. While high immersion may often lead to increased presence, an ardent gamer playing a 3D game on a desktop may feel present in the environment, even though there is a low level of immersion. In realistic virtual environments, especially those used in training where the knowledge obtained from the VE needs to be carried to the real world, presence might be a crucial factor.

In their paper about an experiment using tri-dimensional chess, [SlaterChess] Slater et al present interesting results about the effect of immersion and presence on task performance. While increased presence might lead to increased satisfaction on the part of the user, increased presence may not always benefit the task performance, in fact one can certainly think of poorly designed systems in which, in spite of feeling highly present, the task performance suffers. They also conclude that increased immersion (egocentric against exocentric view) increases the task performance for certain types of tasks.

For the interaction techniques that we developed, we feel that both the egocentric and exocentric views of the system are important. The exocentric view in the VE is not really immersive, and may be only as good as viewed on a desktop. However, for the egocentric view, increased immersion would increase task performance.

The interaction techniques help visualize abstract data. The visualization is a representation given for some numbers based on a metaphor of plotting a graph; there is no real world object to which this visualization maps. Since we aren't dealing with something that is realistic, we feel that increased presence is relatively unimportant in infovis.

1.2.4 Degrees of freedom

Degrees of freedom (DOF) refers to the number of ways in which any object is free to move. For example, a mouse used in desktop systems has 2 degrees of freedom. Trackers used in virtual environments often have six degrees of freedom. They have three translation components (translation along the x, y and z axis) and three rotational components (called pitch, yaw and roll).

In course of day-to-day life, we not only move in three dimensions, but we also tilt the head sideways. A person working with a spanner uses rotation of the wrist. A lot of the actions performed in our daily lives involve multiple degrees of freedom of our limbs and body. Typical desktops, however, offer only two DOF, both translational, and no rotational degrees of freedom. Desktop systems use a contrived metaphor such as the popular Window-Icon-Mouse-Pointer (WIMP) metaphor, which overcomes a lot of the limitations of the 2DOF desktop system. Using immersive virtual environments we have the potential to use more degrees of freedom offered by the system to make the interactions more natural and intuitive.

However, six degrees of freedom may, in VEs, be a little too overwhelming. Even though the real world is 3D, VEs do not offer all the cues that the real world offers [Brooks88], which makes it hard for users to understand 3D in VEs. VEs can use some strategies that may help to perceive the 3D world better, such as two-handed interaction, multi-sensory feedback and head tracking [Hinckley94].

Not all tasks require all 6 degrees of freedom. Interaction techniques should analyze what degrees of freedom are needed for performing the task, and should restrict the degrees of freedom only to those that are necessary. For certain applications there might be a mix of 2D and 3D interaction techniques [Bowman3DUI]. It is necessary to design interaction techniques that take advantage of the DOFs in VEs while keeping in mind the problems associated with too many degrees of freedom in VEs.

1.3 VEs for Infovis

1.3.1 Advantages of VEs over desktop systems

Immersive VEs offer new, exciting possibilities for information visualization. First of all, there is one more real dimension on which information can be visualized. Even though the graphics in VEs are displayed on a 2 dimensional surface, VE displays often have the capability to render in stereo. In case the display is not stereo, the 6 degrees of freedom input devices and ability to use natural movements of the head and the body are so tightly coupled with the graphics generated that it makes the display seem to be 3D. This in itself could have enormous benefits over a 2D desktop. Visualizing a 3D model on a 2D desktop can have problems such as inadequate depth cues. Immersive VEs offer the ability to use the three dimensions in a 3D environment, thus potentially removing the problems presented by desktops.

An added advantage could be immersion that could give an enhanced realistic effect, and improve spatial understanding and orientation. In section 1.2.4, we introduced the

concept of degrees of freedom. 6 DOF trackers can be used to track the head motions and hand movements. Head tracking allows natural motions to get a different view. Moving the head to change the view is more natural than panning using mouse or cursor keys. This potentially eliminates the need for contrived interaction techniques imposed by the WIMP metaphor. Hand tracking allows the user to have natural motions for manipulating objects. Hand tracking also gives the user more freedom, more control and ease for manipulating objects. The intuitive nature of these techniques could possibly make them more efficient.

It is sometimes said that 3D does not lend itself to intense comparative analysis of data because of problems such as distortion arising from perspective view and occlusion. However, by using motion and giving enough feedback, it is possible to use 3D as an accurate and useful tool for decision-making. James Clark, the founder of SGI, once said, "To make 3D work, you need to make it move".

1.3.2 Interaction techniques in VEs

There are some good applications for data visualization in Virtual Environments. These applications allow the user to load complex scientific data and render a visualization based on the data. The users can then manipulate the entire dataset. For data visualization, the complete data set is more important than an individual data point. The analyst is often already aware of a formal relationship between the different parameters visualized. The visualization helps the analyst understand the interaction and relationships within the parameters better.

Infovis differs from data visualization because we are interested in understanding the complete data set, in identifying trends and correlations between data points that may not have any obvious correlations. We are also interested in being able to drill down, visualize subsets and often get specific information about a single data point. Filtering of the data allows visualizing subsets of the data. Identifying a few points or individual point can be achieved through query techniques. All this needs to be done in real time, with the user getting a visual representation of his actions of filtering and querying.

Infovis thus demands a lot of interactivity. VEs lack applications that are made specifically to interact with datasets in order to explore and understand the data for the purposes of information visualization. VEs are often realistic, and data visualization applications in VEs are usually not interactive enough. For the purposes of infovis we described, there is little you can do except visualize the data.

One reason why most current applications have limited interactivity is inadequate interaction techniques. There simply aren't any well-defined interaction techniques in VE systems that are perfectly suited for information visualization. The WIMP metaphor for desktop systems is now almost a standard metaphor for user interfaces on desktops. Familiarity with interaction techniques makes it easy and convenient for people to use one application after another on desktop systems. Most infovis applications developed for the desktop thus use the standard windows interaction techniques that people are familiar with.

We now have the hardware capacity to render complex scenes at runtime. We have the computation power to process large amounts of data all within the real-time constraints imposed for achieving 50 frames a second in virtual environments. There are toolkits and libraries to facilitate application development. Due to this, we can see a lot of good applications out there already that facilitate visualization, albeit non-interactively. The only missing link in our attempt to develop good interactive applications is a way to interact with the system in order to implement the level of interactivity we need. In absence of standard techniques in VEs, it makes sense to use interaction techniques that are well suited for the kind of task performed. This thesis is an attempt to identify and develop some such techniques.

1.3.3 Use of immersion for data having spatial attributes

VEs are often used for creating synthetic experiences of real world. Even as VEs are often used to visualize properties that have inherent spatial attributes, there is a lack of empirical evidence to show that visualizing something in a VE would be beneficial if the data has any attributes that are inherently spatial in nature (e.g. walls and furniture in the architectural walk-through). Experiments are needed to find out if the presence of spatial attributes has an influence on the effectiveness of a VE system. This would mean an understanding of the characteristics of data that make it more suitable for visualization in a VE.

1.4 Motivation

1.4.1 Motivation for using VEs to visualize information

Consider the following scenario:

Consider a census dataset of different cities in the US and ratings about some of their attributes, crime rate, cost of housing, economy, etc, in the form of a huge spreadsheet. Trying to analyze this and find trends and co-relationships is a daunting task, almost impossible because of what can easily be thought of as too much numeric data. Information overload is a term we hear everyday.

Bar graphs, scatter-plot and other forms of graphs help one understand more about trends and co-relations and also help one to get a big picture of the dataset. However, with static graphs, one can only observe a limited number of attributes and hence one would need a large number of static graphs. Also, it is hard to see how one graph is related to another. For example, it would be hard to guess where the two points that have a high crime rate in the scatter plot are in the 3D graph.

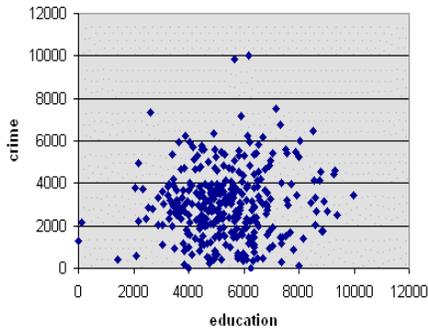


Figure 1.1 2-D scatter-plot showing information about some cities

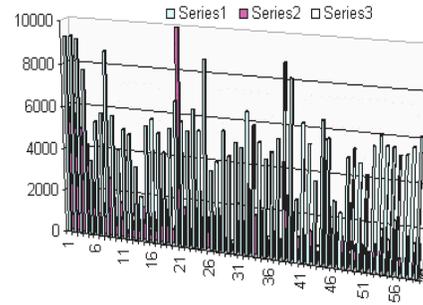


Figure 1.2 3D column graph

Interactivity is the key feature in desktop-based applications such as ‘Spotfire’ [Spotfire] that allow you to change the attributes viewed and get various views of the dataset. You can even view 3-Dimensions on three axes.

However, there is anecdotal evidence that shows that it might be cumbersome and confusing to view 3D on a 2D monitor. Viewing 3D in 2D might be occluding, and may not be able to use the third dimension to the fullest potential. Manipulation done with the mouse and/or cursor keys by dragging to pan and zoom may not be as simple and intuitive as some manipulation that can be done in virtual environments using tracking. Most importantly, a 2 dimensional input device, namely a mouse, is used to select a point in 3 dimensions. This could be ambiguous and inaccurate.

Immersive VEs thus offer an exciting potential for doing information visualization. Natural interaction is more intuitive. Magic techniques can enhance the capabilities of the system, and can be intuitive as well. For example, the use of flying for navigation is a magic technique that allows the user to travel in three dimensions, something s/he could not do in the real world. However, this magic technique is still direct, intuitive and easy to understand. The intuitiveness is because while these techniques are magic in the sense that humans cannot perform them in real world, the ideas themselves are not foreign to the user. Users become familiar with them by observing other things around them, or because of stories and cultural clichés (for example, magic carpets, broomsticks for flying).

Certain magic techniques are useful for power users who can use techniques that violate the assumptions made, but are intuitive enough to be useful quickly [Poupyrev96]. The ability to view 3D data in 3 dimensions, with intuitive natural and magic techniques, to interact with the data is a strong motivation for doing infovis in VEs.

1.4.2 Motivation for “information rich VEs”

[BowmanVenue98] defines information rich VEs as “virtual environment applications that allow users to access embedded information within an immersive virtual space”. It goes on to say, “Due to the richness and complexity of this environment, efficient and easy-to-use interaction techniques are a crucial requirement.”

The need for visualizing more information within an existing VE application can be illustrated with the following scenario.

Bob, an architect, is working in a virtual environment (VE) designing a large complex building. The application allows him to do a walk-through, occasionally making some changes and modifications here and there. At one point, Bob notices that one wall would be under a higher stress than the other, and hence wants know the thickness of the wall and the material of which it is made.

With most current VE systems, Bob would have to exit the immersive VE, look up data in books or online resources and then re-enter the VE and continue with the work. Quitting and re-entering the VE breaks the sense of immersion, and the feeling that Bob had of being present in the building is shattered. Obviously, this is unsatisfactory. The experience would be greatly enhanced if Bob could visualize this data within the VE system itself and use some easy interaction techniques (ITs) to understand more from the visualization, without having to quit the environment.

There exists a need to visualize more information within the VE system than what is currently being visualized. However, there aren't many standard techniques being used to do this. Experiments are needed to find out if the presence of spatial attributes has an influence on the effectiveness of a VE system. This would mean an our understanding of the characteristics of data that make it more suitable for visualization in a VE.

Data about interior design is realistic in the sense that at least some of its attributes, the position of walls and other objects in real life, can be mapped to some spatially identical object in a VE system. However, there are other attributes of this data such as the strength of the material, or cost of an object etc that need to be visualized as well. On the contrary, if we try to visualize Census data, or stock market data, attributes of this data do not necessarily have any real representation in 3D. This data is abstract in the sense of not having a spatial representation in the real world.

Once we, as VE researchers, know about the characteristics of data that make it more suitable for viewing in virtual environments, we could utilize this knowledge of data representation as well as these interaction techniques to show additional information to the user besides the realistic visualization in an existing VE application. This research would lead to better visualization within VEs, in which the person using the VE application (called the user), gains more knowledge because of the additional information visualized. This is what is called an information rich virtual environment. This enhanced visualization could be applied to architectural walk-through, medical imaging and computer-aided surgery, to name a few examples.

1.5 Goals

The general goal of our research is to investigate the use of immersion for infovis. Our first goal is to adapt interaction techniques to adapt overview+detail approach for infovis

in virtual environments. We need to explore and evaluate ways for adapting infovis techniques for their potential use in VEs. We want to develop and evaluate ITs to support overview + detail, and also identify some of the potential types of applications that would benefit from such a technique. If we can successfully adapt infovis concepts into VEs, we can use VEs for developing tools for information visualization.

Our second study is investigating how immersion can be useful for visualizing data that has spatial attributes. We can think of this as a step in being able to identify what are the characteristics of the data that make it more useful to be visualized in immersive VEs.

While developing applications, when the kind of application to be developed is known, VE application designers have an idea of the data involved and have to find out an effective representation to visualize the information. This knowledge of characteristics of data would help us choose ITs and representations based on the attributes of the data while developing a VE system.

1.6 Problem statement and hypotheses

The general problem in this thesis is on how immersion can be useful for information visualization. We explore two sides of this problem.

In investigating how abstract infovis can be done in VE, our focus is on exploring interaction techniques in VEs for information visualization. In designing interaction techniques for infovis in VEs, the first question we asked was: “What technique would be useful in VEs? How can we adapt this technique for effective use in VEs?”

One of the most important concepts in infovis is the concept of overview first, then details when required [Shneiderman96]. Our hypothesis is: For a better understanding and interaction with the visualization, VE-specific interaction techniques should borrow from, but not copy existing 2D IT techniques for overview + detail.

The other side of the problem is how realistic VEs can show more useful supplemental information. Our focus here is identifying the usefulness of immersion for visualizing data, and we wish to investigate if there are certain characteristics of the data itself that make it more suitable for a particular visualization.

Our hypothesis is: If the data to be visualized has inherent spatial attributes, then it can be visualized well in immersive virtual environments.

1.7 Our approach

There already are some proven interaction techniques for infovis on desktop applications, but there is anecdotal evidence that techniques for 2D interaction work poorly if they are directly adopted in 3D. Adapting well known concepts in the field of information visualization to VEs would allow ITs to be developed that allow visualization of such information in VEs.

Our hypothesis would be supported with development of usable and effective interaction techniques that would allow use of the O+D concept within VEs. The usability of these techniques would be validated by usability evaluation.

The steps involved are:

- Identify some of the ways in which the O+D concept can be implemented in VE systems (e.g. maps, miniature worlds)
- Develop (a) new interaction technique(s) for O+D support
- Iterate this design based on a formative evaluation
- Evaluate the technique using summative evaluation.

For our second hypothesis regarding the use of immersion for visualizing data that has spatial attributes, we will have an experiment that involves a comparative study in immersive VE and on desktop. The study would involve visualizing an attribute that is dependent on its other attributes that are spatial in nature (e.g.: position in the world). One way to test this is to have a value that is dependent on the user's position in the world, or position of some object that the user can manipulate. We can investigate whether the increased immersion allows the users to understand better data that has some spatial attributes.

1.8 Overview of this thesis

This thesis is divided into eight chapters. Chapter 1 introduced the terms, gave reasons that motivated this study, and stated what the problem was. Chapter 2 covers related work, defines our goals, and outlines our approach. Chapter 3 is about the first part of the thesis, the initial implementations, reasons why it didn't succeed, and the second implementation. Chapter 4 gives details about the first experimental investigation involving user studies. Chapter 5 is a discussion of the results of the first user studies. Chapter 6 is about the second experiment about data representation. Chapter 7 discusses the results of the second experiment. Finally, in chapter 8 we conclude our findings and outline some future work.

2 Related Work

In this section, we discuss some of the relevant related work, in the field of information visualization and interaction techniques. We discuss some of the previous works that directly influence this thesis. We then highlight how our work differs from some of the previous work.

2.1 Related work in Information Visualization

2.1.1 Basic principles

In his survey paper about existing infovis techniques, Shneiderman has taxonomy of some of the basic principles in information visualization that includes a classification based on the task, and the data type [Shneiderman96]. Particularly relevant to our thesis is the taxonomy based on data type, which he refers to as “task by type taxonomy” where he mentions tasks (overview, zoom and filter, history) used for viewing data of different data types (3D data, network data, hierarchical data etc). In that paper though, current examples of tasks that have been used to visualize a particular type are mentioned; however no recommendations have been made to show that the task chosen is suited for the data type. [Card99] is a collection of papers on information visualization, and is an excellent starting point as well as reference book for a study in infovis.

2.1.2 Overview + detail (O+D)

Numerous visualization techniques elaborated the basic concept of overview first; detail when required for infovis, simplest of this is a regular map. Maps have been used for centuries, and continue to be widely used and studied.

An early use of this technique for information was the Dataland system [Bolt 84], in which the user sits in a room with a wall-sized display. The display on the left offers an overview, and the display on the right holds a touch sensitive visual control. The overview and the detail are tightly coupled. In [Shneiderman97] mentions guidelines for designing applications using this technique, one of which is a limit of 3 to 30 for ratio of the sizes of overview and detail. Beyond the ratio, Shneiderman recommends use of intermediate views. Seesoft is a software visualization tool. [Eick92] This uses an intermediate view between the overview (one pixel per line) and the detail (actual software code). Bederson’s PhotoMesa is another fine example of an application of this concept [Bederson01] [BedersonPhotoMesa01], which implements a zoomable interface for organizing photographs and making annotations on them.

All these are examples of spatial zooming. Semantic zooming refers to use of O+D in which the content remains the same but the appearance changes. The overview and the detail view can either be shown in different parts of the screen (space multiplexed), or can be shown one at a time (time multiplexed). Interactive zoomable maps such as mapquest are an excellent example of this. (Note that they are also an example of time-multiplexed implementation) Lifelines [Plaisant 96] use time as a variable on which to base the overview, because it is a property of all events. There is a trade-off with both

these techniques and the design of O+D techniques should carefully consider this trade-off.

2.1.3 3D Visualization applications

A number of data visualization applications and tools have been developed that provide for 3D visualization. Dataspace [Anupam95] is a system for interactive 3-D visualization for analyzing large databases. Dataspace provides multiple layouts, zoom capabilities etc, and however, trying to manipulate 3D objects on desktop by grab-n-drag motion of the mouse is rather tricky. IVEE [Ahlberg95] is an infovis environment that allows the user to use a number of techniques such as maps and star fields and query mechanisms for visualizing a database. The GIS researchers have done extensive research in spatial information systems in 2D and 3D worlds [Laurini92]. These are all dynamic applications in the sense that the user interacts with 3D graphics by using the mouse. Using 3D interactive graphics has been a research area for Xerox PARC. The work by Mackinley, Card and Robertson, [Robertson93] provides excellent examples use of interactive 3D graphics for information visualization.

In all these examples, the structure of the visual presentation is provided by the linear, hierarchical, spatial or networked structure of the data itself. This provides a natural data oriented approach, which is also outlined in the task by data taxonomy [Shneiderman96].

When there is no physical geography to provide a structure to organize the presentation of the data, or when the physical geography is not known, 3D graphs and scatter plots provide excellent means of organizing the visualization. [Wright95]

Spotfire [Spotfire] is a general-purpose desktop application that allows users to load in a dataset of their choice, and visualize it using 2D and 3D graphs. This application is quite simple to work with, yet provides powerful features for visualizing datasets.

2.2 Related work in VE Interaction Techniques

Most of this thesis is about VE interaction techniques, or rather a subset of ITs that is relevant to infovis. [BowmanIT98] “Proposes the systematic study of design, evaluation, and application of VE interaction techniques.” We hence review some research on development of user interface and ITs developed for VE systems.

2.2.1 Travel Techniques

A number of researchers have addressed issues related to navigation and travel both in immersive virtual environments and in general 3D computer interaction tasks. The research by Darken and Sibert has studied way-finding issues [Darken96]. Various metaphors for viewpoint motion and control in 3D environments have also been proposed. Ware et al. [Ware90] identify metaphors for virtual camera control such as ‘flying’. Stoakley et al. [Stoakley95] make use of a “World-in-Miniature” representation as a device for navigation and locomotion in immersive virtual environments.

An overview of various motion specification interaction techniques and their

implementation is described by Mine [Mine 95]. [BowmanThesis] reports experiments in immersive travel techniques and introduces a new travel technique that has advantages over others.

2.2.2 Selection Techniques

Selection techniques can be based on ‘reaching out,’ ray casting, occlusion and hybrid combinations, or multi-modal.

Selecting an object by reaching your hand out is perhaps the most intuitive way. The limitation of the distance you can reach can be remedied by using exponentially scaling function to map the hand position [Poupyrev97]. Some use more indirect methods to extend or retract the arm. [BowmanGrab] An advantage of these techniques is that manipulation can still be done via hand motion.

Ray based techniques, called ray casting [Mine95] involve a ray pointing out from the user’s hand. This is analogous to moving a mouse over an icon on the desktop. Adding constraints, or allowing the ray to “snap to objects can use ray casting accurately to select far away objects as well [Forsberg96]. However, the manipulation of an object selected in this way is not as intuitive as the manipulation of objects selected by touching.

Image plane techniques are hybrid techniques that involve 2D and 3D. [Pierce97] presents a set of ITs based on occlusion. In one of the techniques described, the user selects an object by partially occluding it. This is actually similar to a ray originating from the user’s eye, passing through the hand. However, this is slightly different from the traditional ray casting techniques since in ray casting; the ray originates from the user’s hand or finger.

There are some techniques that use completely unnatural metaphors that are often effective. The world in miniature [Pierce97] uses miniature versions of objects held in the hand to interact with large-scale objects. This technique has been extended by their further research into ‘voodoo dolls’ [Pierce99], in which in which the user creates his own miniature parts of the environment (dolls) and uses two handed interaction techniques to manipulate these. One doll object acts as a frame of reference while interacting with the other doll.

Multimodal interaction techniques such as put-that-there [Bolt80] allow the user to use voice for commands as well as gestures for specifying the destination of the commands.

2.2.3 Menu Systems

[BowmanTulip01] talks about a menu system called the TULIP menu, which outlines a menu system using pinch gloves as input devices. The central idea here is to use each finger as a menu item, and have more items placed in the palm of the hand. The user chooses a menu item by pinching a finger corresponding to that menu item with the thumb. Additional menu items can be accessed by using one of the pinches to scroll within a list of menu items.

Some other types of menus are pull-down menus [Jacoby92] which are identical to their 2D counterparts, and pen and tablet technique [Angus95] which uses a 2D tracked device as a tablet on which 2D user interface components can be placed and manipulated using a tracked stylus.

2.2.4 Usability evaluation of VEs

Usability evaluation of VEs is essential if VEs are to become useful.

Recent research has attempted to apply common HCI design and assessment techniques to VEs. The most common example of this is the summative usability study, in which users do a structured set of tasks within a complete system or prototype system in order to reveal usability problems that can be solved in the next design iteration. This is a task-based approach for evaluating new designs in prototypes. The concept of usability engineering includes guidelines and evaluation throughout the design cycle of a system, and this model has begun to see use for VEs as well [Gabbard98] [BowmanUsability01].

2.3 Previous Work in Info Vis in VEs

The book Information Visualization and Virtual Environments [Chen99] serves as an excellent resource for some of the work related to infovis and virtual environments and combining both.

2.3.1 Maps and miniature models

Angus developed a flat screen environment and extended some of the 2D metaphors into VE using a hand-held virtual tool [Angus95]. This concept was elaborated in the World In Miniature (WIM) [Stoakley95]. It discusses a way to build a miniature model of a realistic environment to facilitate interaction. In the paper, the WIM is a small dollhouse of a 3D architecture. The paper outlines techniques for travel and object selection. WIM offers a small scale “map” of the world, for realistic environments. This was intended for realistic environments, whereas our interests lie in visualization of abstract information. Our implementation of overview+detail has been influenced to a great extent by this work. Later in this thesis, (see section 3.5.4.3) we compare and contrast our approach with the classic WIM approach.

2.3.2 Infovis applications

There are not a lot of current applications for infovis in immersive VEs. VR Vibe [Benford95] creates a visualization of bibliographies for information retrieval. Users specify keywords in 3D-space. Representations of the documents are then displayed in the space according to how relevant each document is to each of the keywords (this relevance is computed by document matching algorithms). The position of a document depends on the relative importance of each of the keywords to it [Snowdon95].

The LEADS system developed at University of Nottingham [Ingram95] [Ingram96] applies concepts based on urban planning for often abstract spaces of information and database visualization. The system uses a city metaphor based on districts, nodes and edges connected by paths and landmarks to facilitate formation of cognitive maps to

avoid getting ‘lost’ in information space. LEADS system exemplifies how using an easy to understand metaphor can simplify information visualization using immersive VEs.

2.3.3 Information rich virtual environments

Though most VEs have been simulations of real world environments such as an architectural walk-through, some VE systems have attempted to show additional information along with the main application. The Virtual Venue [BowmanVenue98] project, for example, used audio as well as textual annotations. Annotations offer a way to make an information rich virtual environment.

2.4 How our work differs from existing work in this field.

Very little research has been done in the use of immersion for infovis. Infovis in VEs has hitherto largely unexplored area of research. None of the research that we know of is in using immersion for visualizing graphs and scatter plot.

Our visualization application, called Wizard, is essentially based on the concept of maps and world in miniature, the concept of having a small scale representation of a large object. Maps and miniature models have been used but they have never been used for visualizing information that is actually abstract or that does not have an actual 3D representation. In infovis, the representation of a point in space has no inherent meaning. In a scatter plot, the user ‘understands’ information about a point because of the skills the user possesses to understand graphs and scatter plots. Previous applications of miniature models did not attempt to extend their work for visualizing abstract information.

The application that we develop, Wizard, is an application that uses a miniature model of the data set for getting an overview of the data. It consists of a hand held miniature model of a multidimensional scatter plot. Moreover, not only is the miniature linked to the detail model, the reverse is also true, which demonstrates two-way brushing and linking capabilities. The use of miniature model is to facilitate the overview first, details on demand approach of infovis.

Since there is a lack of abstract visualizations in VEs, there is no previous research specifically for the development of VE interaction techniques for infovis. It is a niche that has not been investigated previously. Our research attempts to fill in this gap of research in VE interaction techniques.

Based on our experience with our own proprioceptive senses, we often assume that VEs would be better in visualizing data that has natural spatial representation. While it is argued that this might be useful when the application demands presence, there has been no attempt to investigate whether immersion really helps the users get a better understanding of the environment when there is information that has spatial attributes or is dependent on spatial attributes.

Our research is novel in that it explores a previously uncharted niche of development of applications and interaction techniques for infovis in immersive VEs. It is an attempt to provide experimental proof of whether immersion is useful for task performance in certain types of tasks.

3 Design and Implementation of interaction techniques

One way of implementing an O+D concept is to have two models of the system, a miniature version that you can use to manipulate, and a large version that you can see. In case of a traditional desktop application, this could mean a two-window display wherein one window contains an overview. The visualization in the second window is linked to interactions within the first window. On a desktop, some of the screen real estate is spent in getting an overview of the entire visualization, while the actual visualization occupies a bulk of the space.

3.1 Implementing Wizard

While interaction techniques are an important part of the environment, they are not complete on their own. There needs to be some environment in which we can use the interaction techniques. Moreover, the task of visualizing information is complex, and is often a task that can be decomposed into several smaller tasks, each of which can require different interaction technique. In order to provide a seamless mechanism for the tasks in information visualizing, we needed to create a single environment that serves as a test-bed environment for trying out the various interaction techniques.

We developed this test-bed environment and called it Wizard (pun intended).

In this chapter, we discuss our first implementation of this application (Wizard 1.0), and highlight some of the drawbacks of this model. Our second implementation (Wizard 2.0) attempts to overcome the drawbacks of the previous implementation. We then present details about the interaction techniques that we used. In this chapter, we use Wizard 1.0 and Wizard 2.0 while referring to specific implementations, and simply call it Wizard when we are referring to both in general.

3.1.1 Wizard

Wizard provides a way to visualize data in the form of a scatter plot. While the application currently reads a single dataset from a fixed file, it can be easily changed to be able to load data from any data file. Data points can be represented in the scatter plot, and the position of the point can be used to represent three attributes. Additionally, two more attributes can be represented using color and size of the point.

Wizard provides capabilities to allow the user a representation for an attribute, and the user can then customize the representation to suit his/her needs.

3.1.2 Dataset

In this implementation, we used a dataset about 350 cities in the US, rated on the basis of 9 different parameters such as education, crime rate, cost of housing etc. This dataset was suitable for our purposes since it had a sufficiently large number of data points; each point had 9 attributes. It is a perfect example of a dataset that can be visualized using a scatter plot. More details about the dataset are in the section about the environment, in the

chapter on the design of the experiment (see section 4.2).

3.2 Initial implementation

3.2.1 Basic components of the application

In our initial implementation, we identified three components: visualization, miniature, and interaction. To adapt these three components to VE systems, the main visualization is “out there” in space around the user. The miniature representation is attached to the left hand, at a location slightly above the left hand, as shown in picture [Error! Not a valid link.](#). In case of a 3-dimensional visualization of data, such as a 3D scatter plot, it is possible the user loses his/her spatial orientation. The user’s location is marked on this miniature model as well, and this helps the user get spatial knowledge as to where s/he is in the visualization. The miniature overview is similar to the world in miniature introduced by Stoakley, Pausch et al [Stoakley95].

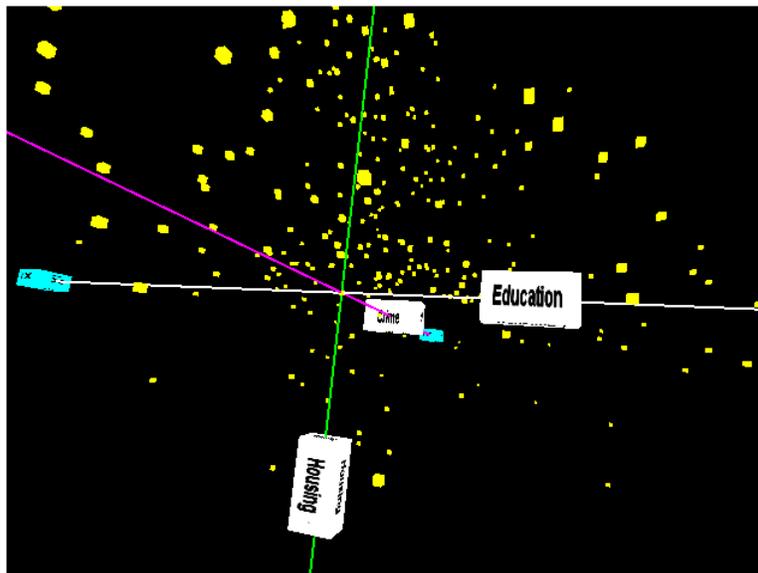


Figure 3.1 Overview attached to the left hand showing distribution of 350 cities based on education, cost of housing and crime rate ratings

The right hand is the interaction hand, used as a multiple functionality tool. Using pinch gloves on the right hand allows a richer set of functionality. A rich set of menus is placed on the right hand in a TULIP menu manner. In this menu system, the fingers of the hand can be pinched to select a menu item. More menu items are displayed on the open palm, and can be accessed by pinching the “Next” menu on the pinky. The menus are context sensitive. The default menus allow the user to navigate, select and deselect points, or change the attributes that have been visualized. Once a few points are selected, then the menu changes to a set of actions that can be done with the selected items.

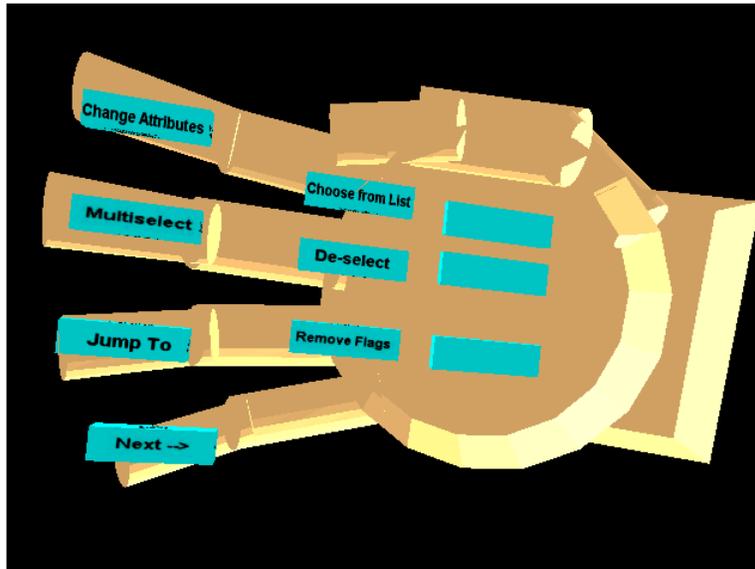


Figure 3.2 Tulip menus - Menu items placed on the fingers of the right hand, and more menu items in the palm

The right hand can also be used within the overview. When the right hand is close to the origin of axes in the overview, it changes to a smaller pointer that allows the user to select things within the overview.

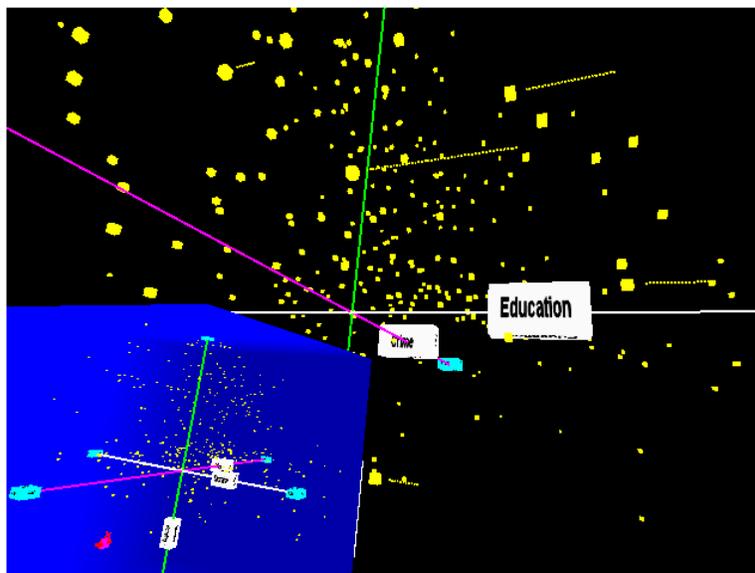


Figure 3.3 In the detail view, the scatter plot surrounds the user in form of a star-field. The user can also see the overview in the blue area in the corner.

3.2.2 ITs implemented

The functionality of the system and the various interaction techniques that were provided are as follows:

3.2.2.1 Changing view

This is basic navigation within the VE system. This can be done in several different ways.

- By holding the index finger pinched, the user can navigate in the direction of the hand. This is useful while navigating short distances in the detail view.
- The user can move the miniature version of the user, the doll, in the overview, and then the user is translated smoothly to that point in the visualization.
- When a user selects a particular point (by choosing it in a drop down list), he can choose “Go to point” and is smoothly moved to that location.

3.2.2.2 Selecting

When the right hand of the user is close enough to any object (the graphical representation of a city is an object, which is a simple cube), the object gets highlighted (turns grey in color). The user can highlight objects this way in the overview as well as the detail. When the user’s hand is within the range of the overview, it changes to a small cursor to help choose an object in overview. The user can choose the ‘select’ menu item for selecting an object that is currently highlighted.

Another way of selecting, particularly useful while trying to select multiple objects, is to specify the first point, and then drag out a box-shaped volume. All the objects that are inside the volume defined by the box are selected. This can be done both in the overview as well as in the detail view.

A third way of selecting is choosing from a scrolling list. In this dataset, the city names are displayed in a scrolling list on the left hand, and the user can scroll through this list to select a particular city.

3.2.2.3 Rotating

While this seems to be a simple task, it is important to identify an interaction technique to rotate the miniature in a way such that the 6DOF does not confuse the user. By attaching the overview to the left hand, the user is able to rotate the overview to get different views. This direct manipulation of the overview is also very intuitive and easy to use. The overview and detail view are not directly linked spatially; rotating the overview doesn’t have an effect on the detail view.

3.2.2.4 Flagging

The user can flag a particular set of points, this is useful in conjunction with changing attributes, or while navigating, and helps to keep a particular point in focus while performing other operations on it. The flagged points are represented with a different color (white) so that they appear distinctly different from other points.

3.2.2.5 Changing attributes & their representations

This allows the user to change what representation shows what attributes. The user can choose to change attributes, and then specify what representation (x, y or z

position, or size or color of objects) is to be used by what attribute (amongst the attributes specified in the dataset).

3.2.2.6 *Zooming*

The user can select a small area to be visualized (by using multiple-selection technique), and then choose to zoom in that. When the user selects the zoom option, the new dataset will be the subset of the complete dataset that was selected. The new dataset is shown with same attributes represented.

3.2.2.7 *Viewing details*

Once an object is selected, then the user can choose the ‘view details’. The details about the object appear on the tablet that is attached to the left hand, and so the user can place the left hand at a comfortable position to view details.

3.2.2.8 *Getting help*

When no object is selected, the tablet attached to the left hand shows context sensitive help, corresponding to the menu items that are placed on the fingers (the ones that can be directly selectable).

3.3 Drawbacks of the first implementation

3.3.1 Observations made during pilot testing

During our pilot testing, we found that some of the interaction techniques were quite helpful in trying to do the infovis tasks, but some others had some drawbacks.

1. The overview was a very useful tool for trying to view trends and using just the overview could do a lot of the infovis tasks.
2. The overview occluded the detail view sometimes. At other times, the detail mode was an unnecessary distraction while trying to view the overview.
3. There was also a problem about mix up, in which it was hard to make out whether an object that is seen is a part of the overview or a part of the detail mode.
4. The way the overview and the detail view were linked for navigation using the doll in the overview in the first implementation was inconvenient. Interacting with the doll was easy, but not very accurate.
5. Selecting in the overview was very difficult. It was hard to be precise enough to select an object in the overview.
6. The functionality of multi-selecting some points, and visualizing only those points was more like a filtering technique, and not zooming technique.

3.3.2 Inferences drawn from the pilot tests

A lot of these issues seemed to suggest that the way the overview+detail model was implemented could be improved. The users were unable to get a very good mental model of the way in which the overview and the detail view were related to each other.

- Let’s consider the problem of occlusion. The overview had to be made distinct from the detail view, such that the user won’t get confused between the two and

one view won't occlude the other. This implied that either the user should only see one view at a time, or the two views should occupy separate but fixed real estate in the view. Especially when the user wanted to view the overview, the detail view was not necessary and in fact was often unnecessarily distracting.

- The mix-up between which objects were a part of the overview and which were a part of the detail view can be traced to the lack of feedback for what constitutes the boundary of one view. We need to show clearly where the boundaries of overview ends and the detail view starts.
- Manipulating the doll was another concern. The problem once again traced to inadequate feedback. When the user manipulates the doll and moves it from one point to another, there is no feedback of what the view will be from the dolls position in the overview in real-time. Putting it simply, it was hard for the user to understand what s/he "will see" once based on the doll's position and orientation in the overview. At this point, the question we asked ourselves as designers of the system was "What exactly are we trying to achieve with the doll". It seems like the 'doll' was an unnecessary metaphor and it is better to have a first person point of view for navigating in the overview rather than a third person (god's eye view).
- A way of solving the problems related to selecting in the overview mode was to change the size of the overview. There is very little we can do about the jitter in the trackers and the inherent lack of accuracy in 3 dimensions.

Our second implementation is an attempt to solve some of the problems with Wizard 1.0 that we detected, based on some of our inferences of the pilot study and rationale.

3.4 Second Implementation

3.4.1 Basic components of Wizard 2.0

In Wizard 2.0, we introduce the concept of two modes, an overview mode and a detail mode, without the use of doll-based manipulation.

The user starts off in the overview mode, in which the overview is attached to his/her left hand, which s/he can manipulate. The user does not see the detail view at this time. The user is allowed to interact with the overview, and can manipulate the overview, select points, change the attributes represented, and so on. When the user wants to investigate more details, he can choose to "jump" to the detail mode.

In the detail mode, the user is floating in a 3D scatter plot identical to Wizard 1.0. The overview is placed at a constant offset so that it always appears in the bottom left corner of the view. A blue colored box that demarcates the overview from the detail view encloses the overview. The overview in the detail mode is linked to the detail view, so that the axis in the overview and the detail view are always aligned. A red marker in the overview represents the users position in the detail view. This is explained in greater

detail in section 3.5.4.



Figure 3.4 Detail mode- The user sees the overview in the corner and the detail view surrounds the user. The user interacts with only the detail view.

The right hand is used as a multi-functionality tool similar to the way it was used in version 1.0.

3.4.2 How does Wizard 2.0 attempt to solve some of the problems ?

Wizard 2.0 solves the problem of occlusion in the overview mode by allowing the user to view only the overview. In the detail mode, the overview always occupies a fixed position in the corner of the view that is unobtrusive. Putting a blue colored box around the overview, which helps separate one view from the other, solves the problem of mix-up of data shown in the two views.

The problems associated with doll manipulation are entirely eliminated with the “jump.” The user changes from one mode to another using his/her own view, instead of having to use the doll’s view.

3.4.3 Interaction techniques in Wizard 2.0

While complete details about the second implementation and the design decisions we made for the interaction techniques are explained in greater detail subsequently, here we mention some of the interaction techniques that are in the second version.

3.4.3.1 Changing view

This is basic navigation within the VE system. This can be done in several different ways.

- By holding the index finger pinched, the user can navigate in the direction of the hand. This is useful while navigating short distances in the detail view.

- If a user has selected a point and has moved away from it, and wants to get back to view the point, s/he can choose “Go to point” and is smoothly moved to that location.
- If the user chooses a city based on its name, that object gets selected and the user is automatically moved to a point in front of the object that represents the city.

3.4.3.2 *Jump*

To switch between the two modes, the user uses the “jump.”

The user can manipulate the overview in the overview mode using the left hand. If the user wants to jump to the detail mode, the user pinches the “Jump To” menu. The position of the user in the detail mode is based on the position of the overview with respect to the user’s viewpoint in the overview mode. The user’s position in the display is such that the users view remains unchanged. The user now sees objects in the detail mode just the way they appeared in the overview. The difference is that the 3D scatter plot now surrounds the user.

3.4.3.3 *Selecting*

Selecting objects in the detail mode is identical to the way it was done in the previous implementation. However, selecting a point by touching it is only available in the detail mode, since it was hard to select this way in the overview.

3.4.3.4 *Rotating, flagging and changing attributes and their representation, Viewing details and getting help*

These remain unchanged in the second implementation.

3.4.3.5 *Filtering*

The user can select a small area to be visualized (by using multiple-selection technique), and then choose to “filter data.” On choosing the “filter data” action, the user views only those data points that were previously selected. Thus the user can focus on viewing only certain points while ignoring the others. Thus the user “filters” some of the data to be visualized.

If the user wants to visualize the entire dataset again, s/he can choose the “Show All Data” action.

3.5 Interaction Techniques for Infovis

In this section we attempt to describe in greater details the different interaction techniques that we developed for Wizard 2.0. We explain the options we had for different interaction techniques that we could use, or different ways of implementing an IT. We explain our design decisions and reasons why we took them.

3.5.1 Menu System

In the related works section (see section 2.2.3), we discussed various menu systems.

Applications use menus as a way of allowing the users to choose options or perform actions.

The pen and tablet metaphor is useful when there are a large number of UI objects to be placed on a toolbar of some sorts. The greatest motivation for using this in any application is the fact that most users are already familiar with 2D menus and UI widgets. However, the user needs to use both hands for interaction; one to hold the tablet and the other to hold the stylus. In our application we had the overview attached to the left hand we needed a menu system that will use only one hand.

We can use drop down menus, since the user can select a drop down menu with only one hand. Once again, familiarity with drop down menus in desktop applications is a strong motivating factor for their use. However, drop down menus take up fixed real estate from the view all the time. The amount of space the drop down menus would take is fairly large in a VE, where the display has a low resolution and low pixel density. Moreover, every time the user needs to choose a menu item, s/he needs to view the drop down menu, which can break the feeling of presence.

The TULIP menus were a way of achieving exactly what we wanted. We implemented a slight variation of the tulip menus on just one hand if needed. The user could simply move the hand away when he didn't need the menu, and thus this menu system will not occlude the view at all times. Moreover, once the users were familiar with the menus, they are able to choose menu items from this menu simply by pinching the correct fingers, and even without actually "seeing" the menu. This menu system does not get in the way of the user when not needed, and can be used with just one hand, and is the perfect menu system for our applications.

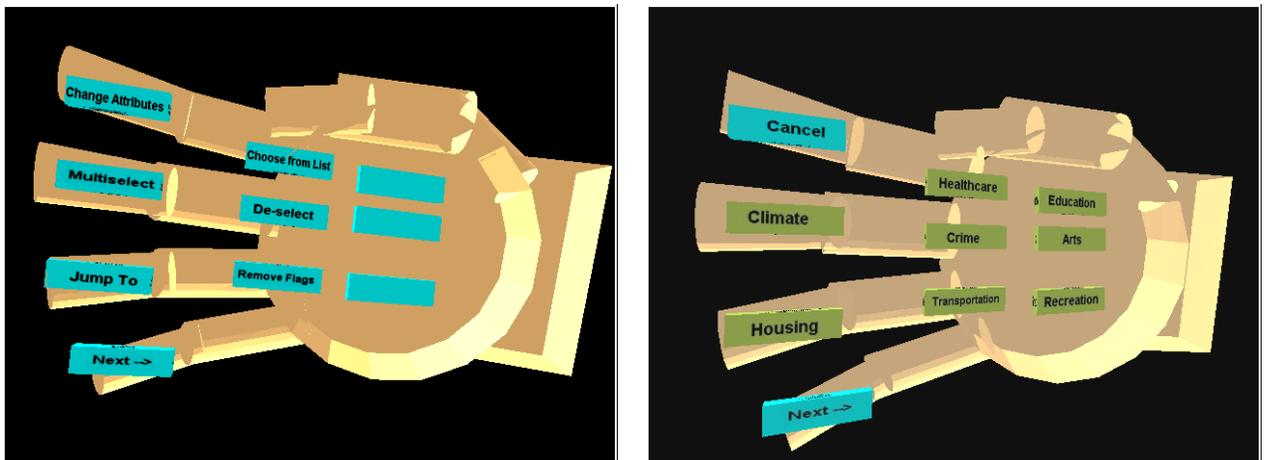


Figure 3.5 Examples of tulip menu used in Wizard

3.5.2 Navigation

In cases of applications like this, in which the user is immersed in a large size scatter plot,

the user needs some way of getting from one point to another. Moreover, the user selects a point by reaching out to touch it. Often the user needs to move closer to the object so as to reach out for it, and thus the user needs to navigate very often.

One of the inherent ways of navigation in a VE is natural navigation, i.e., allowing the user to use his natural movements to move in the simulated world. The user can walk around to move in the virtual world. Using head motions, the user can find out and browse the dataset as he would visualize and view a real world.

However this motion is restricted to small distances due to the limited range of the tracking devices. Although wide area trackers are available, they may still have a far shorter range than the virtual world. The user is tethered to a limited range even more because of the cables and wires. More importantly, this motion can be excessively tiring and there needs to be some better navigation mode.

However, this form of motion may have merits when it comes to rotation and changing directions. It may be simple and natural to change directions by turning your head or your body around.

In Wizard, one form of navigation is the “jump,” which is the transition from the overview mode to the detail mode. For moving to large distances, or different views, this is perhaps the most effective method of navigation. We shall discuss this in greater depth while discussing the overview + detail interaction.

Since the jump is the intended form of navigation for larger distances, it is expected that the user will use the other navigation methods within the detail view only for short distances, typically trying to reach out for a point they wish to select. There are two possible ways of navigating within the detail view.

- Gaze directed steering – motion is in the direction in which the user is looking. Essentially, the user moves “forward” in the direction s/he is facing.
- Hand directed steering – the user points his hand and then moves forward in the direction pointed by the hand.

Gaze directed steering has certain advantages, the most important of which is that there is a good feedback since the direction of view is also the direction of motion. In this application, however, the user often wants to keep focus on the object selected, or some particular object of interest while navigation in a different direction. For example, consider a user who wants to find out which city has a lower value on two of the axes than a particular city. The user may want to navigate in the detail view without losing focus of the particular city that needs to be fixed point of reference.

Hence we preferred using hand directed steering to gaze directed steering, because the user can navigate without losing focus.

3.5.3 Selection

The user has to select the points before s/he can do possible actions on them. For retrieving detailed information about one particular point, getting exact numeric data or information about the point, there has to be some way of selecting points. Some of the tasks in infovis may require the selection of more than one point. For example, a user may want to select a whole bunch of points that are close to each other, which means that they are similar to each other on the basis of the attributes visualized, and mark them. Later by changing attributes, the user could understand how the same points are related, based on some other attributes.

Various techniques for object selection in virtual environments have been studied, some of which we discussed in the related works section. We implemented some of these in this application.

The most “natural” way of selection is touching some object within reach. In fact, the sheer simplicity of this technique is one of its biggest advantages. The user simply reaches out in the detail view and if the hand position intersects with any of the data points, then those objects get highlighted. The user can then choose to select the object.

To be able to select multiple points, the user can draw a volume and all points that fall within the volume get selected. While selecting a volume, we incorporated a rubber banding effect, in which the volume being selected is shown by a bounding box while it is being drawn out. The objects that fall within the bounding box are highlighted. When the user pinches the middle finger again, the bounding box is finalized.

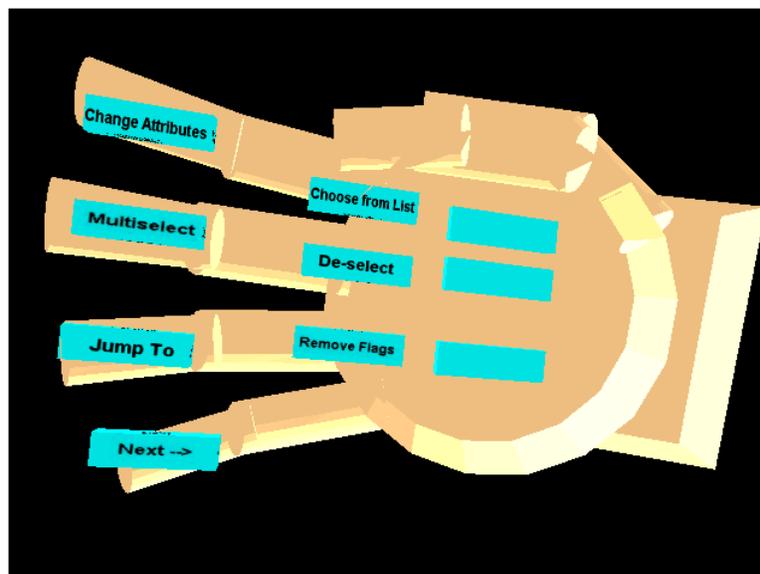


Figure 3.6 Menu showing "Multiselect"

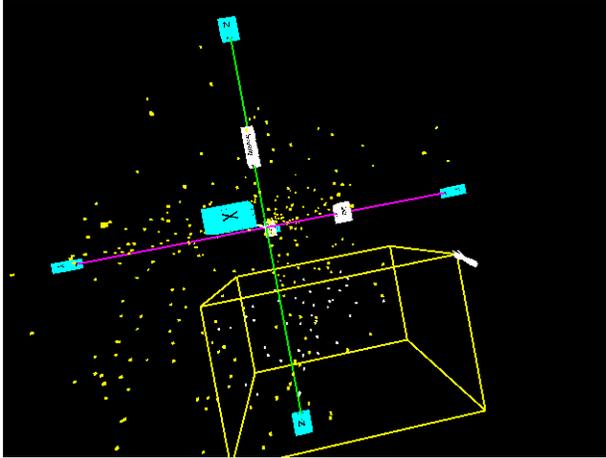


Figure 3.7 Using the right hand, the user draws out a bounding box. All points within it are highlighted

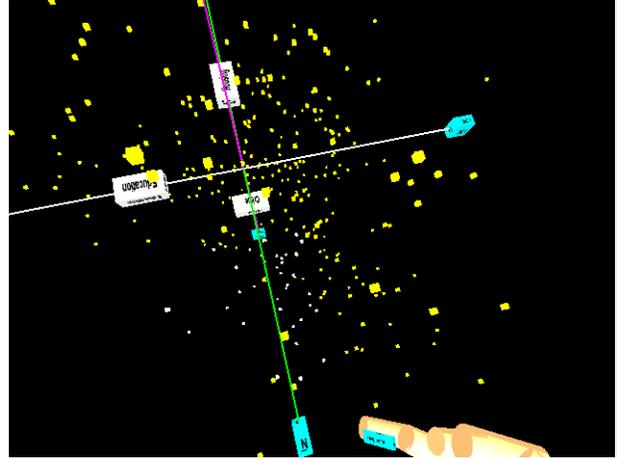


Figure 3.8 On choosing the second point, the bounding box disappears, and all objects within the box are selected

While the multi-selection can be used both in the overview as well as with the detail view, we feel that this feature will be mainly used in the overview mode to do a selection of multiple points on a lower level of granularity. One of the reasons may be the fact that people prefer to be able to see the boundaries of the selection and be able to get a real-time feedback of the various objects selected.

Ability to select by reaching out, initially implemented for both modes, is restricted to detail view. In the pilot tests, we could see that it was extremely hard to select a particular point in the overview by reaching out.

The difficulty of selection in the overview can be attributed to a number of factors

- It was difficult for the user to be precise about his hand positions – particularly with respect to the depth. Users are not able to detect objects closer or further away. They are able to decipher if one object is to the left or right to bottom or top. [Hinckley94]
- The size of the objects was really small and unwieldy. This fact is validated by Fitts' law, which says that the movement time is a logarithmic function of the size of the target if the distance remains constant. [Fitts54] It is much easier to select an individual point in the detail view.
- The tracker had jitter, which added to this inaccuracy.

Based on our own experiences and the observations made during pilot testing, we decided to make this selection technique exclusively in the detail mode.

One possible technique is using occlusion-based techniques for selection, analogous to some of the techniques that have been discussed in the “head crushers” paper [Pierce97]. Another way is to use ray casting [Hinckley94] However, while both these techniques (in fact they are quite identical, although they appear to be different on the surface) are easy and useful in VEs, it is hard to be accurate with these while trying to select one object

amongst a very large number, when the number of objects is in the magnitude of hundreds, or possibly thousands. Hence using techniques such as head crusher may not be the best choice while dealing with such a large number of selectable objects. It presents some advantages, and we are considering working on some modification or adaptation of it in the future.

Yet another way of selecting a particular point is doing this selection based on a known value. This is analogous to selection in a list. We shall discuss this in greater detail in the section on choosing from a list (see section 3.5.6).

3.5.4 Jump

The jump is the most important technique. It implements the very basic philosophy that goes behind the way the overview and the detail view are linked in the virtual world.

3.5.4.1 Implementation in Wizard 1.0

In Wizard 1.0, the overview was always attached to the left hand; a doll represented the user's position in the world. The user could manipulate the doll and choose to move the doll to a different location within the overview, and then the user is smoothly scrolled to that location. This was the preferred navigation method in the initial implementation.

This navigation technique is identical to the one introduced by Stoakley, Pausch, et al, [Stoakley95]. In fact, in that application, the WIM was used mainly for selection and navigation. The navigation was indirect, involving manipulation of a miniature representation of the user itself.

Pilot studies of this implementation brought out a number of problems:

1. The doll showed only the position, it did not show the orientation
2. Moving the doll within the tiny overview could be prone to errors, inaccuracies
3. It could be hard to predict and create a mental model of what the new world will look like from the new position and orientation of the doll.

The first problem was a trivial problem from the implementation point of view, but it might further lead to problems with regards to accuracy. Another fact is that the overview is small in size and even if the doll had the proper orientation, it would be hard to understand it really well due to the small size. Moreover, users often have a problem getting accustomed to the 6 degrees of freedom [Brooks88] and hence, using 6DOF on each hand would only complicate the matters more.

Since there isn't a lot we could do about the source of the second problem, one way to get around it is to be able to avoid it in its entirety if possible. Our second implementation tries to get around the tracker inaccuracies by avoiding accurate selection of small objects by using the "jump" to get to a large-scale view.

The third problem is non-trivial. In fact, the solution to it is perhaps the most important

difference between our first and second implementation.

3.5.4.2 *Relevance to infovis*

In the second implementation, the user views the overview for identifying trends and observing the dataset, but when details are needed, he switches to the detail mode. In this case, unlike the previous, there is a more distinct separation of overview and detail concept into distinct modes. This is where the “jump” from overview mode to detail mode and back out comes into the picture.

In infovis terms, in Wizard 1.0, the two views were more like a miniature view and a blown up larger view that were brushed and linked. In Wizard 2.0, we introduced this two-mode concept. This is more in tune with the infovis mantra of overview first, details only on demand [Shneiderman96].

3.5.4.3 *Implementation in Wizard 2.0*

Since the user starts with the overview mode, we wanted the user to be able to go to the detail mode without losing any spatial orientation. We wanted the user to get an idea of what the detail view will be like, before jumping into the detail view. The third problem led us to realize that the doll wasn't essential at all, as a matter of fact; the users own view could provide the best possible feedback of what the detail view will be after the jump. Hence we came up with the technique to jump from the overview to detail view such that:

1. The user uses the left hand to manipulate the overview to observe what s/he wants to see.
2. When the user chooses to jump, the user is placed at a position such that his/her view remains unchanged.

Since the view remains unchanged, this avoids disorienting the user. After the jump, the main view is the detail, but the user can also get additional spatial orientation by looking at the position of the doll, which is at the position and orientation in the overview, where the user is in the detail. The entire overview itself is aligned with the detail view.

This method of interaction is what distinguishes the miniature overview in our technique from the WIM described in Stoakley's implementation [Stoakley95]. The miniature doll in the dollhouse, for example, had only two translations and one orientation DOF. While visualizing the abstract dataset, we offered the user complete 6DOF to be able to view the dataset any way s/he chooses. We believe that the need for our technique exists because of the abstract nature of the data that does not offer the same cues as the realistic doll house described in the classic WIM. This belief is based on the results of the pilot study, and it will be interesting to see if we can establish empirical evidence to prove this fact.

Our implementation of the jump is similar to the image plane technique described by Pierce et al. [Pierce97] In that implementation, when the user chose an object, a 2 dimensional miniature image of the object selected appeared in the same view, but

attached to the users' hands. In our implementation of jump, the world position of the user is based on the position of the eye with respect to the miniature.

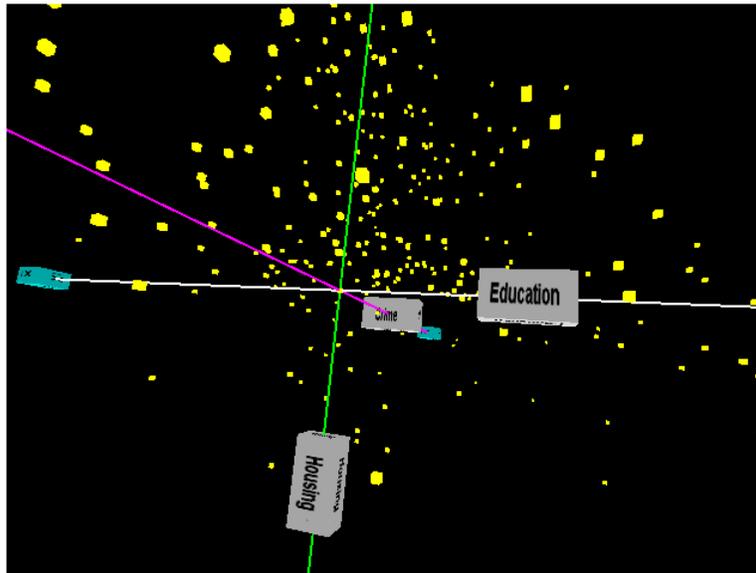


Figure 3.9 This is the way the overview was before the jump

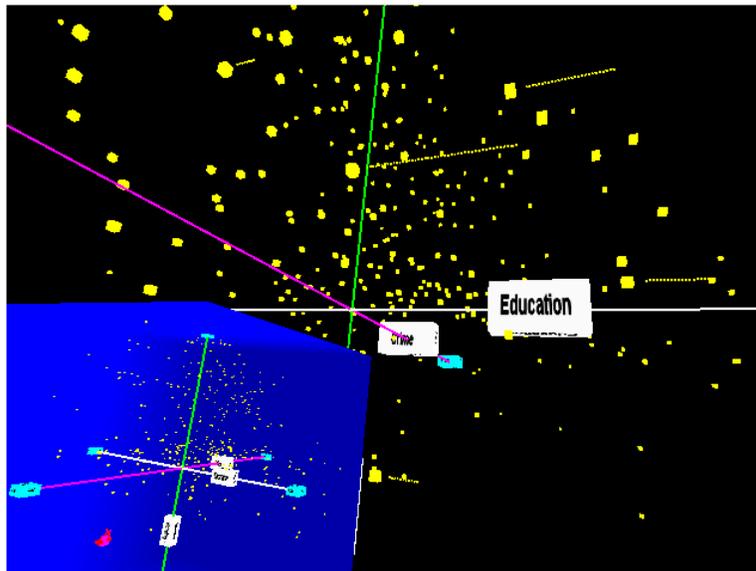


Figure 3.10 After the 'jump', the user moves to a place in the detail which has an identical view of the dataset

3.5.4.4 *Technical details of the jump*

The jump involves some interesting manipulation of the scene graph. The implementation is as follows:

1. Get the relative matrix of the overview in the left hand with respect to the origin (origin object is the "base" point of the "user"), and save this in a matrix (lets call

```

it mResult).
SVE_getWorldMatrix(objOrigin, matOrigin) ;
SVE_getWorldMatrix (objWimPointer,matWimPointer ) ;
SVE_getRelativeMatrix(matWimPointer,matOrigin, matResult);

```

2. Get the relative matrix of the “Eye” object with respect to the overview (lets call this matrix mTranslate).

```

SVE_getWorldMatrix(wim, matWim) ;
SVE_getWorldMatrix(objEye, matEye) ;
SVE_getRelativeMatrix(matWim, matEye, matTranslate);

```

3. Set the last row of the mResult to the last row of mTranslate (effectively, set the position values in mResult to those in mTranslate).

```

for (i=0; i<=2; i++)
    matResult[3][i] = matTranslate[3][i] ;

```

4. Change the matrix of transformation of “Origin” object to the modified “mResult” matrix.

```

SVE_getWorldMatrix(objOrigin, matOrigin) ;

```

5. Calculate the offset of the “Eye” with respect to the “origin.”

```

SVE_getWorldMatrix(objOrigin, matOrigin) ;
SVE_getWorldMatrix(objEye, matEye) ;

```

6. Translate the origin object with the “1 * offset”, (effectively, move the “Eye” object to where the “Origin” object was.

```

for (i=0; i<=2; i++)
    matOrigin[3][i] = matOrigin[3][i] -
        (matEye[3][i]-matOrigin[3][i]) ;
SVE_setNewObjectPosition(objOrigin, matOrigin);/**/

```

3.5.4.5 Jump back – jumping from detail view to overview

The jump back is relatively simple; once again the user can use the left hand to manipulate the overview. The overview gets attached to the left hand with the same orientation as in the detail view. However, we found that it is more probable that the user would move his left hand rapidly and thus it won't really matter which way the overview gets attached to the left hand.

The implementation of jump back is quite similar to the implementation of the jump operation.

Any objects that have been either selected or flagged remain in that state when the application jumps from one mode to another.

3.5.5

3.5.6 Move to Origin

While this is simple to implement, it may be very useful.

The origin of a graph can have possible effect on the way the data is visualized. Sometimes the user might want to do a “shift of origin,” that is, assume some other point is the new origin instead of the current point. One task where this might be useful is the task where the users are asked to name two cities that have their crime rate and housing costs lower than New Jersey, but higher value for transportation from Jersey. While trying to do this task, the user may choose to make Jersey the new origin, and then quickly select the points in the correct octant.

In Wizard, the dataset is, by default, arranged spatially so that the origin of the axis represents the median of the dataset. The position of a point that has a value higher than the median is determined by the formula:

$$\text{pos} = \frac{\text{value} - \text{min_value}}{\text{max_value} - \text{min_value}} \times \text{limit}$$

Where pos = position of the point on that axis

value = value of the city on that attribute

min_value and max_value are the minimum and maximum values on that axis

limit = maximum distance away from origin on the scatter plot on that axis

Similar interpolation is also used for position of a point that is lesser than the median, in such case, the value ranges from maximum negative value and zero.

When a data object is selected, and moved to the origin, the selected point becomes the origin of the dataset, and the rest of the data is spatially arranged with respect to this selected point. This may then squeeze data in one half of the axes at the cost of sparse data on the other. However since the entire dataset is abstract, this will not be confusing to the users.

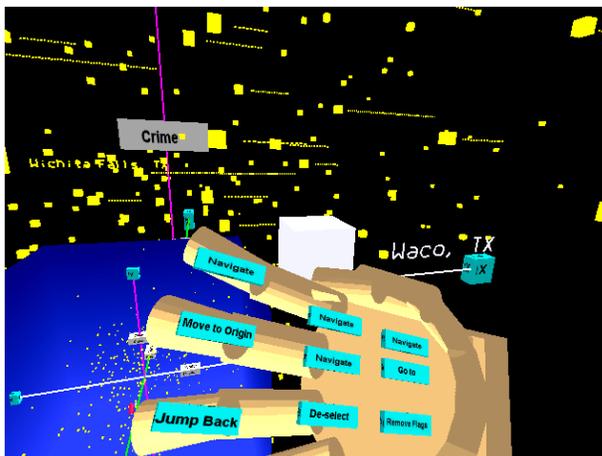


Figure 3.11 A particular object is selected, and the user chooses the 'move to origin' action

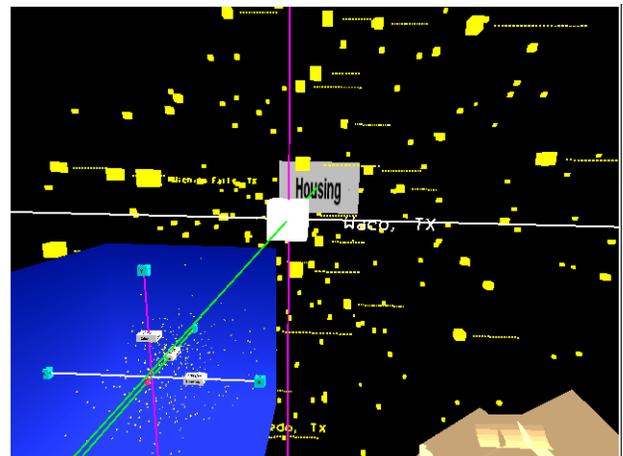


Figure 3.12 After the 'move to origin' action, the selected object becomes the new origin, and other points are automatically sorted

3.5.7 Choose from list

For selecting one option from a large number of options, some of the 2d components often used on desktop settings are:

1. Static List boxes
2. Drop down list boxes
3. Combo boxes

Drop down list boxes are used to reduce the clutter on the desktop, where they can be a compact GUI widget except when the user wants to choose one of the options, they drop down and occupy more screen space. This means that the use of drop down list boxes is a two-step process, where in the user first activates the drop down, and then scrolls through the list to choose one option. While this can be a useful feature while building complex GUIs such as a rich set of GUI widgets on a tablet while using a pen and tablet metaphor, the extra activation step may be unnecessary when the UI is simple with just the list box and options to scroll or choose. Combo boxes allow text entry along with allowing the user to choose one option. Since the entire application does not involve any form of text input, this feature does not present any advantages over drop down list boxes in this application, while still retaining the drawbacks.

In this application we implement a list box for choosing a city based on its name. To choose a city, the user chooses the “Choose city from list” option and then the right hand menu system is replaced by a list box that allows the user to see 6 options at a time, out of which one of them is highlighted. Pinching the thumb and the pointing finger to scroll up, and pinching the thumb and the pinky to scroll down do the scrolling. The highlighted option can be selected by pinching the thumb and the middle finger.



Figure 3.13 The 'choose from list' displays a scrolling list using the pinch gloves

Although this application does not demand being able to select multiple cities from the scroll list, this feature might be useful for other applications that might need more than one selection in the scroll list. We already have some ideas about how we would like to do this but we haven't implemented those in the current application.

3.5.8 Change attributes

The entire dataset may have more attributes than can be visualized at any one time. There is also an issue of how much the user can understand without being overloaded. Moreover, different ways of representing attributes may be differently suited for different tasks.

In Wizard, the three axes offer one way of representing data. Besides these, users can also use color and size to represent data.

If the user chooses to represent an attribute with color, then the color value is computed for each point in the scatter plot. The coloring is done using the R (Red) and G (Green) values for color. The median of the dataset gets median values for red and green, thus appears to be yellow. Values higher than the median have more red value, where as values lower than median would have higher green values.

For using size, we calculate a scale factor for each point in the scatter plot based on the value of the attribute that is being viewed using size. The least value is scaled by a factor of 1, the highest value by a scale of 5, with all others falling somewhere between.

To change the representation of any attribute, the user chooses the "change attribute" menu item. The menu changes to show the different representations, x-axis, y-axis, z-axis, color and size. On choosing one of the representations, the menu changes to show possible attributes.

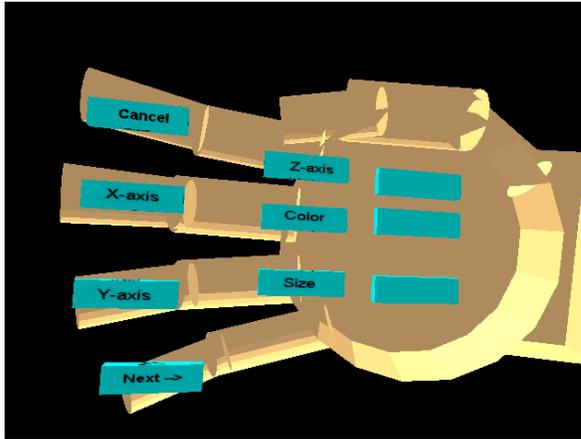


Figure 3.14 On selecting the 'change attributes', the user is given a choice of representations to choose from

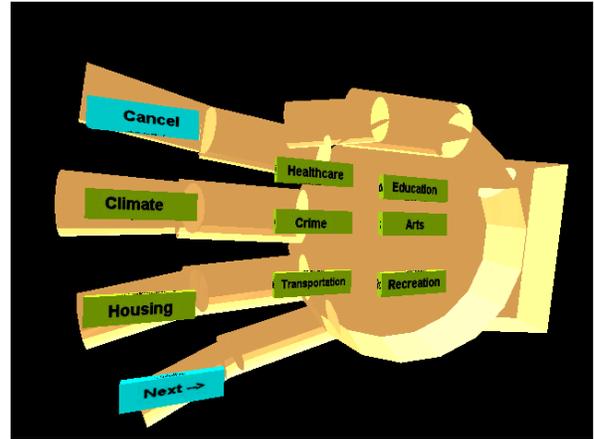


Figure 3.15 On choosing the representation, the user can choose the attribute to be visualized

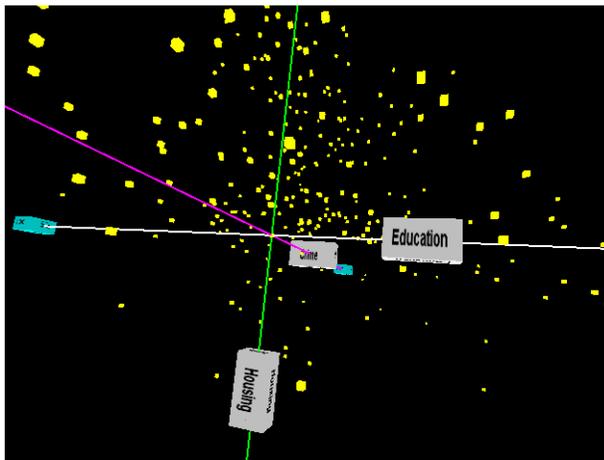


Figure 3.16 This is the default visualization. X, Y and Z axes are used to visualize three attributes

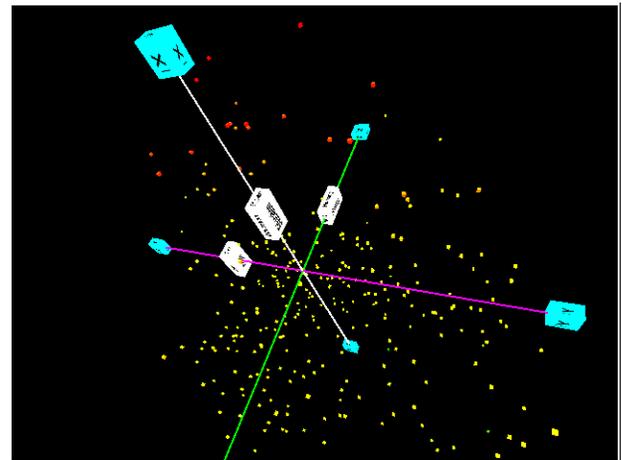


Figure 3.17 In this visualization, color is used to represent the fourth attribute

Sometimes, the user may not want to use a particular representation to view anything. For example, the user may want to view a 2 dimensional plot with color to represent the third attribute. For this, Wizard has a special option to choose “none” to represent a particular axis.

3.5.9 Flagging a point

When people want to draw attention to a particular object, or point, it's common practice to highlight it, label it distinctly, or in some way flag it. One of the tasks involved was choosing two cities that were quite identical to each other based on some attributed visualized. The second part was to see how they were related based on some other attributes. What users often did was to identify the two cities, flag them, change attributes and then visually identify whether the two cities were similar or different based on the new set of attributes.

When a point is selected, it may be flagged by choosing the “Set Flag” action. This changes the color to white, which is very prominent. The point remains flagged when the mode is changed from Overview mode to the O+D mode.

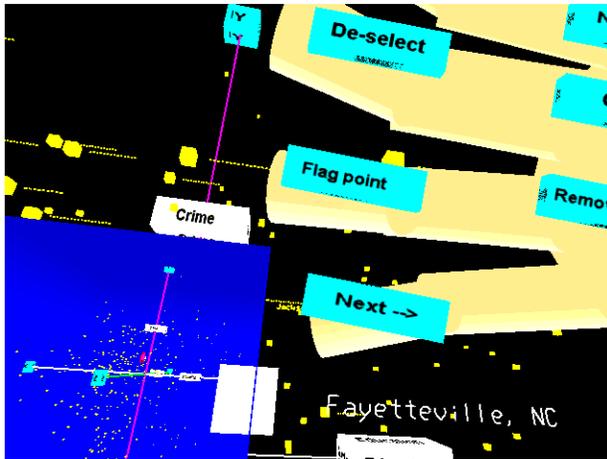


Figure 3.18 An object is selected, and the user chooses 'set flag'

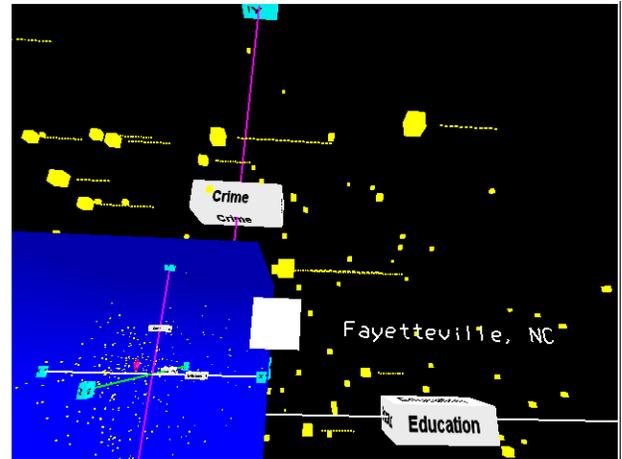


Figure 3.19 The flagged point appears bright white, which helps mark it and identify it easily against the black background

3.6 Summary

In this chapter we introduced our implementation of Wizard, an application that serves as a test-bed environment to test the interaction techniques we developed. We describe our initial implementation, explain the reasons we decided to change some of the interactions, and describe the second implementation. We then explain, in greater detail, each interaction technique that we developed.

The interactions we developed were evaluated based on the user studies. The experiment to evaluate the ITs and the results of this experiment are explained in chapters 4 and 5.

4 Experiment 1:

Experiment to evaluate Interaction Techniques

In the previous chapter we discussed some infovis interaction techniques that we developed for use in immersive virtual environments. We evaluated the usability of these ITs through user studies. This chapter outlines the experimental setup for the experiment to evaluate the usability of interaction techniques.

4.1 About the experiment

4.1.1 Purpose

This experiment is to validate our hypothesis that the 2D infovis interaction techniques can be adapted for use in 3D environments for visualizing information in virtual environments. The experiment evaluates each of the interaction techniques we have designed by having the user use them while performing some task assigned.

4.1.2 Brief outline of the experiment

In this experiment, the user has two views of a dataset about 350 different cities in the US visualized on the basis of some of their attributes such as housing rate, climate etc. The user is expected to interact with these views using the techniques provided. Each task assigned focuses on a small subset of interaction techniques designed.

This is a typical task-based usability study that is centered on the work tasks users of this application currently perform, or will perform while using this application. Usability problems arise when there is a mismatch between the user's understanding of the task and the inherent system model. [Wilson 95] In this experiment, we are interested in the usability of the interaction techniques; task-based usability studies are effective for testing usability of new techniques. We believe that usability of the interaction technique is crucial towards its use for performing tasks.

However, it is important that the techniques are useful for the purpose for which they have been developed. We wished to investigate the usefulness of these techniques for performing some of the tasks in infovis, and one way to get this information was to evaluate the task performance by collecting some quantitative data. We set targets for the performance of tasks using our techniques. We decided to use this approach instead of a formal empirical experiment to evaluate the usefulness of the system.

4.2 Method

4.2.1 Subjects

The user study to test the usability of the interaction techniques involved 10 users. The users were unpaid volunteers, all people at Virginia Tech. Their average age was 25

years. There were eight males and two females. The user population was equally split between people who were novices (4 males and 1 female) against experienced users (4 males and 1 female) of virtual environment. We wanted to find out if the familiarity with the VE setup affected the user performance.

4.2.2 Apparatus and implementation



Figure 4.1 A person wearing the HMD and using pinchgloves in front of a tracker

The HMD in the experiment was the Virtual Research V8. It supports a resolution of 640x480, with a sixty-degree diagonal field of view. The HMD presented biocular images to the user. We used Polhymus Fastrak tracking system to track the head and both the hands of the user. On the right hand, we used a Fakespace pinch glove. The application was developed using the SVE toolkit [Kessler 00] and ran on a PC running Windows 2000.

4.2.3 Environment

The environment is like a three-dimensional scatter plot of data points. This was visualized from the data set of around 350 cities in the US and information about some of their attributes. You can interact with this data, move about in the environment, get an overview to observe trends and try to get information from the visualization. The system includes menus and other interaction techniques, which you will learn about as the experiment progresses.

The 3D data is about various cities in the US, and ratings for some attributes about the cities. The nine rating criteria used are:

- Climate & Terrain
- Crime
- The Arts
- Housing
- Transportation
- Recreation
- Health Care & Environment
- Education
- Economics

For all but two of the above criteria a higher score is better. For Housing and Crime criteria, however, a lower score is better.

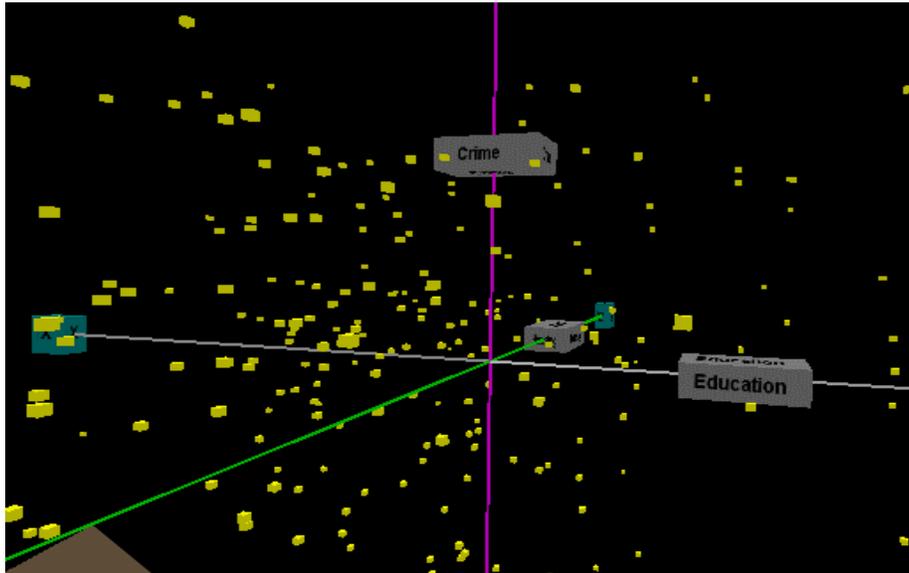


Figure 4.2 3D scatter plot of cities with axes labels

7

The 3D (x, y, z) position of the data represents three of the attributes above. The origin represents mean values in the data set. A point with a negative value for a certain attribute has a value lower than the mean in the dataset for that attribute. The positive axes have a label indicating what they represent.

Additional attributes can be visualized using size (smaller size means lower values) or color (green means lower values, red means higher values).

4.2.4 Experimental design

The study was composed of 12 tasks that involved finding correlations and trends in the data set, obtaining more information about specific cities, etc. Each user performed all the tasks.

There were three phases to the evaluation. At the end of each set of trials, we asked questions regarding the user's level of comfort at that time. They were asked to give a rating between 1 and 10 to assess their level of arm strain, hand strain, dizziness, and/or nausea.

4.2.5 Procedure

After reading and signing the informed consent form, the volunteers were asked to fill in the pre-experiment questionnaire (see Appendix B.1) that contained demographic information such as age, gender, and occupation (or major field of study), and the subject's use of computers and prior experience with VEs. After that they were asked to go through the instructions sheet, and then those unfamiliar with the VE equipment were told about the basic setup and hardware.

4.2.5.1 Phase I: Exploring the environment (15-40 minutes)

The users move around the environment to understand its layout and to obtain views from various positions, and to be able to identify the way they could interact with the overview of the dataset, and then are able to drill down to details.

During this phase, the users explored some of the interactions by themselves. Some users were more proactive than others in trying out different menu choices, and seeing how those affected the visualization. However, the application itself was complex, with numerous interactions. While it was useful to see the users explore the functionality by themselves, even the proactive users did some interactions ad-hoc. They skipped some actions by themselves.

For evaluating task performance, it was absolutely necessary that all the users were introduced to all the functionality offered by the application. Hence, after the users had explored the application by themselves, the experimenter walked the users through the functionalities they had missed. By the end of this phase, the experimenter made sure the users had adequate knowledge of the capabilities of the application.

The users were free to ask questions at this stage. They were encouraged to talk aloud about their reactions to the different features.

We feel that information visualization is in itself a complex task that requires people to have certain knowledge about the data, as well as certain skills to perform the task. While it is always nice to have a novice users start using any system without having to train them, we felt that a little training was needed for the users to start using our application and make use of all the features provided.

4.2.5.2 Phase II: 1st set of Tasks (15-30 minutes)

The first set of tasks was not timed. The experimenter read each task out and the users were asked try to think aloud how they would perform a given task. The main intention of this set of tasks was to get qualitative data and a better understanding of the user's thought process.

The users were told to attempt exploration and to perform the task by themselves. However if they were stuck on a task, they could ask the experimenter for help.

In the previous phase, the users had learnt about the different features of the application. In this phase, the users learnt how to use these features for a specific task. It gave the

experimenter a chance to understand the thought process, the way the users decomposed the tasks and the rationale for performing the task in the manner in which they did. This phase allowed the experimenter to collect qualitative data about the users' perception tasks and the interaction techniques.

The tasks themselves are listed in appendix B.2. Some of the tasks require the user to visualize the entire dataset and identify trends and correlations. Some other tasks require the user to be able to identify a particular point or a set of points in the dataset based on certain criteria. Others implored the user to filter data and work with a subset. Thus the tasks the users performed are a good mix of the tasks the user will perform with any infovis application. They allow the user to perform a typical set of tasks required for visualizing information.

4.2.5.3 Phase III: 2nd set of tasks (10-15 minutes)

This phase was a set of timed tasks. The type of tasks was similar to the ones in Phase II. The users were encouraged to try to do the tasks as quickly and efficiently as they could on their own, without interruption. By this time, it was expected that the users were proficient in the use of this application for performing infovis tasks. The tasks in this phase were similar to the ones in the previous phase.

This phase enabled the experimenter to collect quantitative data about the experiment that was used for evaluating the usefulness of the ITs.

At the end of the experiment, the users were asked to fill out a questionnaire, and then to participate in a brief interview session. They were encouraged to make comments, suggestions, or ask questions they had about the system, techniques, or devices.

4.2.6 Data collected

Objectively, we measured the time for completion of the tasks for all tasks in the Phase III of each trial. We also measured the number of errors made. The experimenter recorded time from saying "Go" after reading the instructions until the user was able to complete the task. The time required for completion of task is a measure of efficiency with which the user is able to perform a task

We also measured the number of errors made. The errors could be major or minor. Minor errors were the errors associated with scrolling too much in the scroll list. The major errors were incorrect answers, when the users found trends that were incorrect, or didn't find trends and co-relations when there were some prominent ones. The minor errors were usability errors. The major errors are very crucial to the usefulness of the system, since a major error meant that the user was unable to understand and comprehend information from the system.

We measured the comfort level (see Appendix B.3) from time to time, and also got objective data about the user's satisfaction, and relative ratings on various interaction techniques from the post-experiment questionnaire (see Appendix B.4).

The subjective data was collected by observing the user perform various tasks and by taking notes during the tests. The tests were also audio-recorded to facilitate transcription, but the experimenter made notes during the experiment. Critical incidents that occurred during the evaluations were noted and oral comments and feedback were recorded; some of the salient comments are listed during the analysis of the results in the next chapter.

4.3 Conclusion

We started this chapter with a brief outline of the experiment. The chapter then covers the method, the subjects, environment and the experimental design. We elaborated the procedure we followed and the data that we collected from the experiment. The next chapter is a detailed analysis of the results of the experiment.

5 Results of experiment 1

The previous chapter discussed the experimental setup and method. In this chapter we discuss the results of the experiment. We discuss the outcome of the experiment not only in terms of the time required for tasks, but also based on the questionnaires and comfort ratings. The observations made by the experiments during the experiment are also recorded and are important for this analysis. We also mention comments and quotes made by the subjects that were a part of the dialogue during the “think aloud” process, or even during the experiment.

We draw inferences based on all this data, and attempt to support these based on some of the results.

5.1 Basics

Drawing conclusions based on the results of an experiment is based on a careful analysis of the data obtained from the experiment. Here, we present some data to support our inferences. The data we used was obtained from a number of sources, timings, questionnaires etc.

5.1.1 Pre-experiment questionnaire

The pre-experiment questionnaire (see Appendix B.1) was more of a demographic survey. Points of specific importance to us were the answers on previous experience with VEs, and previous knowledge of infovis applications. The users rated their knowledge on a scale of 1 to 5, where 1 meant no experience and 5 meant expert users. They also described their knowledge in words.

5.1.2 Timings & Errors

The experimenter recorded the timings and errors. Some of the tasks consisted of multiple parts. In such cases, the experimenter recorded time for completion of each part, and the total time was the sum the individual times of all parts.

5.1.3 Post-experiment questionnaire

The post-experiment questionnaire (see Appendix B.4) contained two parts. The first part was a set of 11 questions regarding specific interaction techniques. The users rated these for three criteria, namely, ease of learning, ease of use, and usefulness in infovis. Each was rated on a scale of 1 to 7, where 1 meant low and 7 meant high.

The second part contained 8 questions about the entire environment. Each of these was also on a scale of 1 to 7. For all but the question about comfort with the equipment, 1 meant a low score and 7 was a high score.

5.2 Observations and Inferences

In this somewhat lengthy section, we analyze the data we have, draw conclusions, and

make recommendations based on the data and our observations.

While the detailed explanation of these conclusions is discussed later in this section, some conclusions we draw are as follows:

- Direct manipulation of the overview provides a low learning curve and high ease of use. This leads to an increased understanding of the dataset, and an ability to visualize and comprehend the entire dataset (See section 5.2.1 for details).
- Our adaptation of the overview + detail technique is successful for infovis in virtual environments. With an initial training, users find the two modes of interaction easy to use and useful for performing infovis tasks. Users efficiently form a mental model of the way the two modes are related once they get used to it. With only a little training, the users can use the two modes for interaction to perform infovis tasks (See section 5.2.2 for details).
- Selecting objects in the detail mode by reaching out is fairly simple and intuitive. Navigating in the detail mode was not easy for everyone however. While our implementation of detail mode works for some users, it is not easy to use for all. Ray casting techniques offer a potential solution for some of the problems the users faced in the detail mode (See section 5.2.3 for details).
- Scrolling lists allows users to choose a known value more easily. Our implementation of the scrolling list using pinch gloves has a low learning curve, is easy to use and provides the functionality necessary for choosing a known value (See section 5.2.4 for details).
- Users find our adaptation of the menu technique easy to use. Users found it simple to change the attributes using the mechanism we implemented. Users can use three spatial dimensions and colors to represent different attributes (See section 5.2.5 for details).
- Choosing multiple data points and filtering techniques has a potential use in infovis. Further study is needed to be able to generalize the “filter data” option using a novel query technique beyond ordinary multiple selection (See section 5.2.6 for details).
- Using the “move to origin” technique results in greater understanding while performing tasks in which we need to make comparisons with a known fixed point based on certain attributes (See section 5.2.7 for details).
- Help should be provided only initially, and should be non-obtrusive. An adequate training phase can reduce the need for help. Help should be provided for the novices and should get out of the way of the experts. Feedback should be provided for each and every action. Use of colors and sounds enhances the feedback (See section 5.2.8 for details).

- Users have a good ability to break down a complex task into a series of smaller subtasks. Different users often have varied ways of performing the same subtask, but eventually all of them are able to achieve the goal (See section 5.3.4 for details).

5.2.1 Direct manipulation of overview

This feature was an undoubted success. In the training phase, the first thing the users were taught is the use of the tracker for manipulating the overview. The users picked up this almost instantly, and remarked that it was easy to get views of the dataset.

5.2.1.1 Task performance

While most of the tasks involved the use of this direct manipulation of the overview at some stage or another, a couple of tasks were almost entirely dependent on this technique, and the users' ability to understand the dataset using this technique.

In Task 4, the users were asked to explain the relationship between three attributes and identify the outliers. All the users were able to understand the relationship and also identify some of the outliers.

In Task 6, the users had to concentrate on a particular region in the scatter plot (cities with high value for two attributes), and were asked to identify characteristics based on two other attributes for this subset. They were to also identify any trends or correlations. All the users were able to identify the characteristics, and 8 of the 10 identified some trends and relationships even while visualizing 4 attributes simultaneously.

Figure 5.1 shows a graph of the timings on Task 4 and Task 6. We notice that while Task 6 seems more complicated than Task 4, but for most subjects, it took less time to complete. However, we should keep in mind that Task 4 involved identifying outliers, which meant jumping into detail mode to name the outliers. This took a little more time. Task 6 could be completed with just the overview mode. The average time taken for Task 4 was 168.5 seconds, and the average time for Task 6 was 148.8 seconds, which was less than the 3 minutes we had set for target. VE experts only barely outperformed novices; we could conclude that this technique was equally easy for novices and experts.

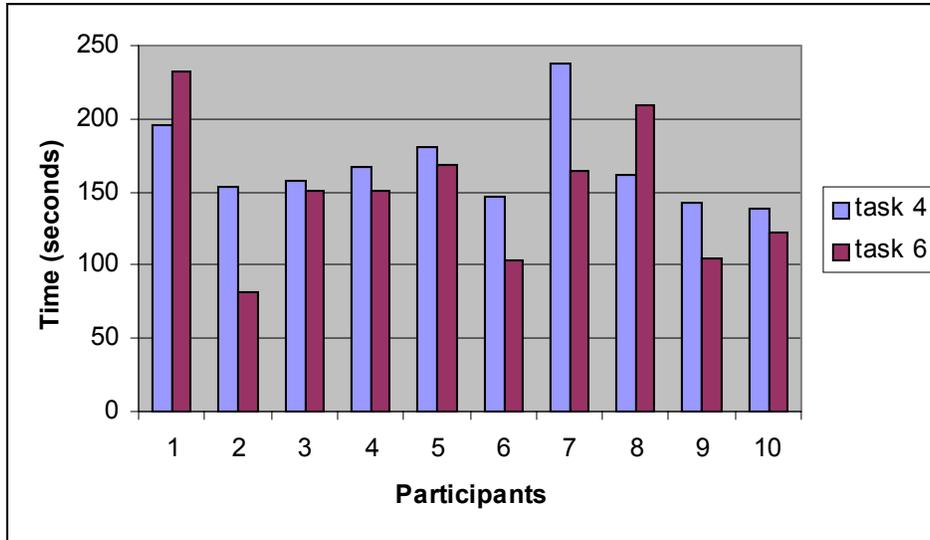


Figure 5.1 Time taken for completion of task for tasks related to identifying trends

5.2.1.2 Questionnaire findings

Even in the questionnaire, the users rated this direct manipulation highly and rated it above average in all the ratings for the ease of use and ease of learning as well as usefulness in infovis. They also gave high ratings when asked if the overview allowed them to get insight into the trends and get the big picture about the dataset. Figure 5.2 shows the ratings the subjects gave about their ability to get different views of the dataset. Participants 1 through 5 are novices to VE, where as the participants 6 through 10 were experts. Here we noticed that the ratings given by the experts (average ease of use 6.2, average ease of learning 6.8, average usefulness 6.4) were higher than their novice counterparts (average ease of use 5.6, average ease of learning 5.2, average usefulness 6). This may be due to the fact that the VE expert users were more familiar using 6DOF trackers, so it was easy for them to use and learn.

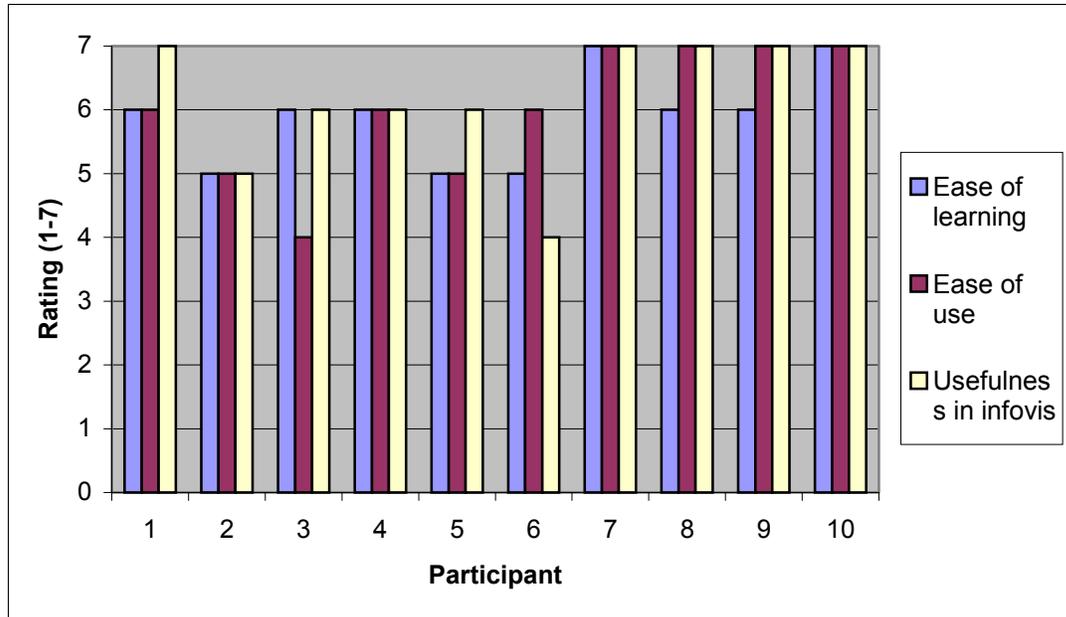


Figure 5.2 Ratings on ability to get different views of the dataset by interacting with the overview

5.2.1.3 Observations and comments

As the users were given tasks, the reactions and the comments made showed that the users found the overview extremely easy to use, and very useful for the tasks. Almost every user remarked that they liked the direct manipulation for overview. Some of the comments we recorded illustrate the point that most subjects made in some way or another. “I like the directness of the tracker” said one. Another user commented about the speed with which she could interact with the system as, “ (I could) quickly change the view completely, and yet I know what I am looking at.”

5.2.1.4 Conclusions

Based on the quantitative data about tasks, the questionnaire results and the observations, we present our first conclusion:

Direct manipulation of the overview provides a low learning curve and high ease of use. This leads to increased understanding of the dataset and an ability to visualize and comprehend the entire dataset.

5.2.2 Two modes of interaction

As a part of the training all users were told the details of the jump operation, how the users could use the jump action to change from overview mode to detail mode and how to use the “jump back” to change from detail mode to overview. Since almost every task involved changing modes, it is hard to analyze the task performance, as this is a small part of almost every task. However, the questionnaire had a question for this, and we

followed it up in the interview.

5.2.2.1 Questionnaire findings

In the post-experiment, the users rated their understanding of the two modes and ability to interact with them.

Most users rated this low for ease of learning, though they rated it moderately well for ease of use. However, this was rated high on the usefulness in infovis criteria. Figure 5.3 shows the ratings for different participants. Participants 1 through 5 are novices whereas participants 6 through 10 are VE experts. We find that VE experts rated this higher (average ease of use 5.2, average ease of learning 5.2) than the novice users (average ease of use 4.2, average ease of learning 4.2) for ease of learning and ease of use.

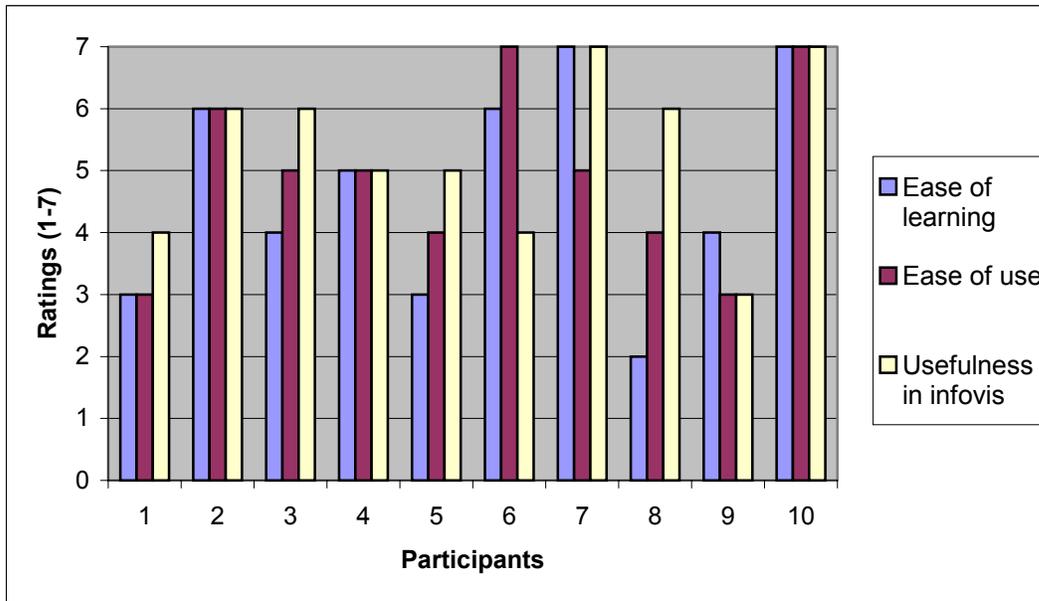


Figure 5.3 Ratings on understanding and ability to interact with two modes

To explain this difference, it is necessary to remember the way the jump was implemented. When the user jumped from the overview to the detail mode, the user was at a location from which s/he would have the exact same view. VE experts, especially those who had used some form of magic technique, not only found it easy to grasp this concept, but most of them also learnt how to leverage this to their advantage. Users who became experts with this found out that they could manipulate the overview so that after the jump, the object that the users were trying to select was just within reach.

5.2.2.2 Observations and comments

While training the users prior to the tasks, the experimenter observed that the novice users took a little more practice jumping from the overview mode to the detail mode. No one had any problems jumping from the detail mode to the overview. All the users could use the jump technique for their tasks, and some of them mastered this technique well enough to be able to jump exactly where they wanted.

5.2.2.3 Conclusions

Based on this we can conclude that:

“Our adaptation of the overview + detail technique is successful for infovis in virtual environments. With an initial training, users find the two modes of interaction easy to use and useful for performing infovis tasks. Users efficiently form a mental model of the way the two modes are related once they get used to it.”

5.2.3 Details view

This section includes navigation and selecting objects in the detail mode. Our implementation of the detail view had mixed responses. From the numeric results as well as by noting the critical incidents, we are able to identify what the users found to be useful in the detail view and what led the users to feel this view was not easy to use.

5.2.3.1 Task performance

Almost all tasks required the user to jump into the detail mode for some part of the task, since selecting a single point was possible only in the detail mode. However some of the tasks required the user to identify his/her position in the detail mode, and then navigate and select particular points in the desired region.

In Task 3, the users were asked to identify two cities that had higher values for some attributes and lower values for other attributes with respect to a particular city. Most users identified a city by choosing from the scroll list, and then in the detail mode, identified which direction to move in. They then identified the two cities that came up in the direction of their sight. Eight of the ten users were able to do this task successfully.

Figure 5.4 shows a graph of the timings on Task 3. The times for Users 4 and 5 are not valid, since they did not complete the task successfully.

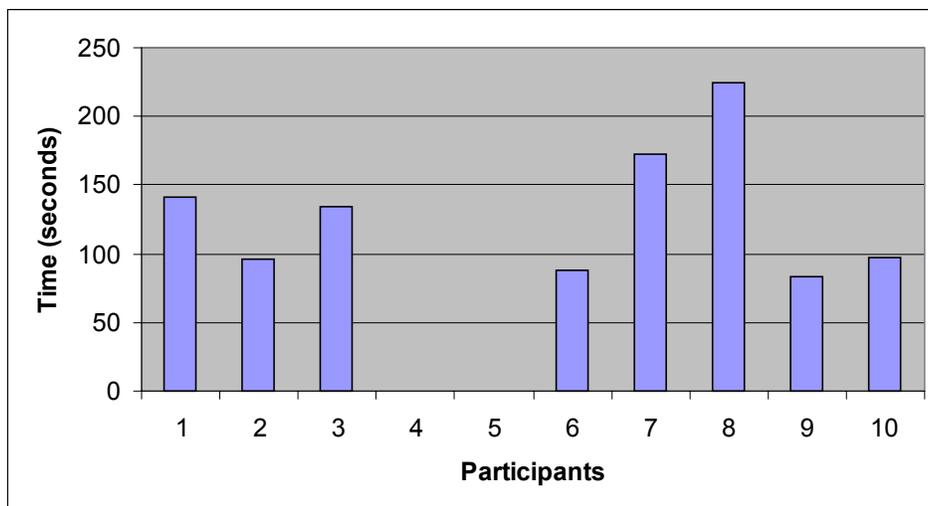


Figure 5.4 Time taken for completion of task 3

The average time taken for Task 3 was 130 seconds, which was more than 2 minutes we had set as the target. Thus we were not able to achieve the target we had set for this task.

All VE experts were able to complete the task successfully, whereas only three of the novices completed it successfully. However, VE experts on an average had a higher time for task completion than the VE novices.

5.2.3.2 Questionnaire findings

The questionnaire provides us with some insight as to why the time required for completion was more than what was expected.

Figure 5.5 shows the ratings on the ability to select by reaching out for an object in the space. This was rated high on the use in infovis; this is obvious because getting details about an individual point is an important task in infovis. However, its ratings on ease of use and ease of learning raise some concern. Some users were not comfortable with selecting objects by reaching out for them.

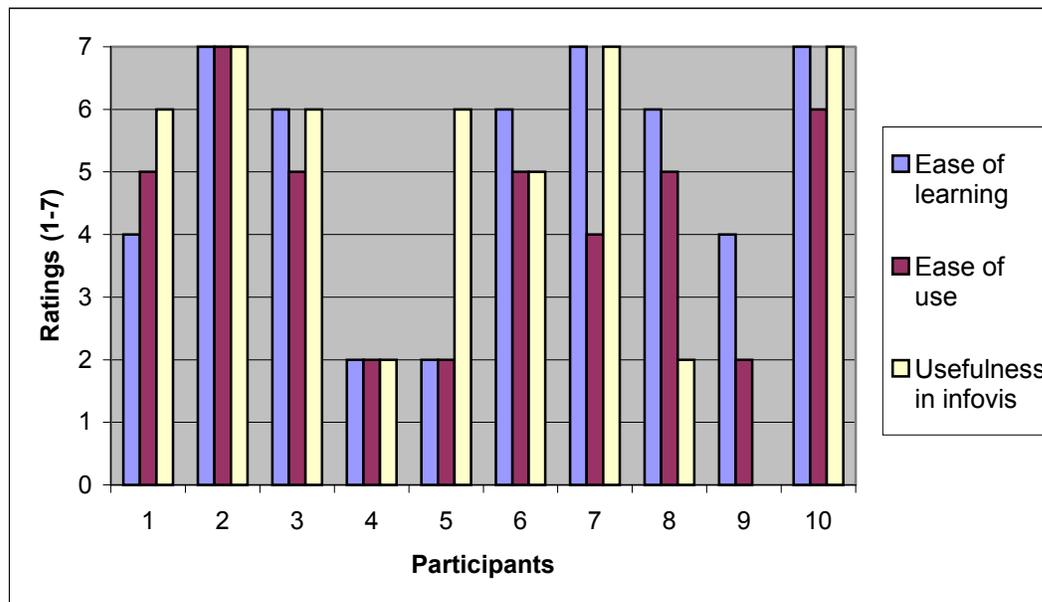


Figure 5.5 Ratings on selecting a single point by reaching out for it

Question 3 in the second part of the questionnaire was about the overview in the left bottom corner of the view in the detail mode. While one user found that useful to get oriented, most users felt that this overview was simply occluding and not useful, this resulted in lower than average ratings for this question.

The problem with this overview was once again the tradeoff between the level of detail and the size. The overview was small and yet showed the complete information; it was hard for the user to understand much from this overview. However, the overview was big enough to occlude the detail view at times; this at times caused the user some inconvenience. One user remarked “Can I hide the overview?”

5.2.3.3 Observations and comments

Explanation for why the interaction in detail mode was not up to the mark can be best explained based on the observations made during the experiment and the comments made

by the users during the interview.

The biggest problem for some users was navigation in detail mode. We had incorporated a navigation using hand-directed steering. However, during the experiment, we observed several things related to navigation. It was easy to notice the discomfort people had when navigating by looking at their actions. When navigation would get too cumbersome, some users jumped back in the overview and started over again.

Some of the problems we encountered are as follows:

- Some users were unable to understand the direction of navigation.

In spite of the initial training phase where they were taught navigation, some of the users expected to be moving forward in the direction they were looking at. Some of them were confused when they moved in a direction that was different from what they expected.

One reason for this is that the tracker was mounted on the back of the hand whereas people usually use a finger to point the direction. Hence the direction that people think they are pointing at is not exactly the direction that the trackers on the hand would indicate.

- Users were sometimes inaccurate.

In a lot of tasks, the users had to navigate in the detail world until they came close enough to select some object. However, sometimes the users continued to navigate past the object. They did not release the pinch at the right time. This was observed more in some users than others. At times, the users were close to an object but not close enough to reach out and grab it. When they tried to navigate closer, they overshot and went past the object. They had to turn back and then navigate again, and sometimes they went past it again. For users that had this experience, this became frustrating. This not only affected their performance in navigation, but also affected their general experience in the detail mode and affected their ability to select objects in the detail mode. Figure 5.5 above shows that certain users rated the selection in detail mode very low. These users experienced greater difficulty in navigation than others.

- Backward navigation was extremely hard.

This was by far the most common complaint, especially when people just went past an object they wanted to navigate close to. Navigation backward required the users to point their hands backward, which was an uncomfortable position. It was also highly inaccurate for most people.

Some of the comments we recorded voice the opinions of a number of other users as well. “Navigating through the space to select a point using the right hand ‘navigation’ button was tough.” said one. “This was the only task I couldn’t do easily.” Another user made an interesting comment that could be a possible addition in functionality. “Is there a ‘move backward’ button?”

We did not notice problems specifically associated with selection. Most people expressed satisfaction in the way they could select an object by touching it. They expressed satisfaction at the feedback they got when the object was highlighted. It was the users that had a hard time navigating that didn't want to navigate close to an object to select it.

5.2.3.4 Conclusions

Based on the empirical evidence as well as observations made, we can conclude: *“Selecting objects in the detail mode by reaching out is fairly simple and intuitive. However navigating in the detail mode was not easy for everyone.”*

One possible way to simplify the selection and navigation in the detail mode would be to use ray casting techniques to select. In this, there would be a ray or a cone coming from the user's hand and the object with which this ray intersects can be highlighted. While ray casting is difficult to implement in the overview where the number of points and the size of objects is small, it is possible in the detail mode where there are smaller number of objects in the view, and when the size of objects is larger.

Ray casting can also be used as a target-based navigation technique. In this implementation, the ray can point to an object that acts as a 'hook' The user can then move to this point. The object can be simultaneously selected. Thus ray casting can be simultaneously used for navigation and object selection.

Another simple modification to the navigation technique that might actually have a tremendous impact is to have a “move back” button that would move the user a couple of steps back from his/her current position. For users who kept overshooting the object they were trying to get closer to, the “move back” offers an easy way to recover from the error.

The problem with the overview in detail mode is basically to do with information overload, there is too much information shown in the tiny overview, to the point of being useless. However, the overview is a useful tool that allows the user to be oriented spatially. We believe that it is a necessary part of the detail mode.

One modification can make the overview more useful at the same time less occluding. The overview can be made smaller, but the data points are removed from the overview. The regions in which there is more data can be represented by a translucent “data cloud.” The user's position in the world and the axes are still shown. This approach has the advantages of requiring less real estate on the screen, hiding unnecessary details about the data in the overview, and not overwhelming the user with too much information.

5.2.4 Scrolling through the list

Our implementation of the scrolling list using pinch gloves met a favourable response from the users.

5.2.4.1 Task performance

In Task 5, the users were asked to identify the city that was most similar to one particular

city in terms of three attributes. All the users identified a city by choosing from the scroll list. They then identified the city that was most similar.

Figure 5.6 shows a graph of the timings on Task 5. All users with the exception of one novice user were able to complete this task in less than two minutes; some of the users performed this task in less than a minute. None of the users made any errors in identifying the correct city.

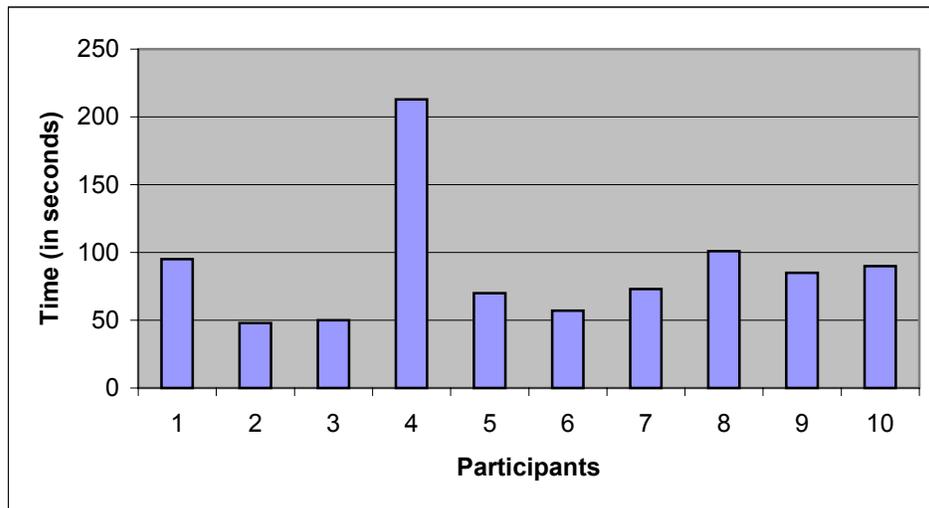


Figure 5.6 Time taken for completion of Task 5

However, there were some minor errors while interacting with the scrolling list. Some users scrolled beyond the desired name and had to scroll in the opposite direction to get to the correct name. We recorded these as minor errors. Figure 5.7 shows the errors made by the novice users while performing Task 5. None of the expert users had any trouble using this scroll list, but novice users made some errors.

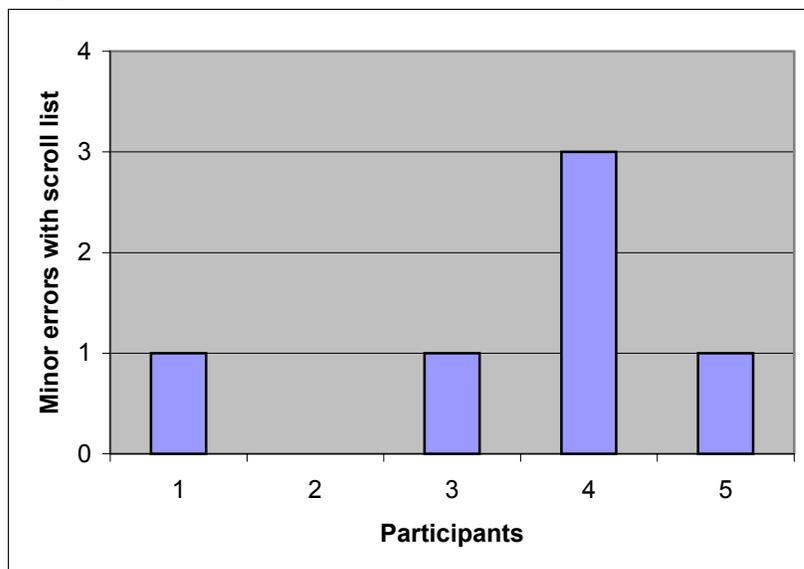


Figure 5.7 Errors with scroll list while performing task 5

5.2.4.2 Questionnaire findings

In the questionnaire, we asked the users about their ability to select a particular city from the scrolling list. All the ratings are above average, with all the users finding the technique extremely easy to learn and simple to use. Users also realized its importance in infovis.

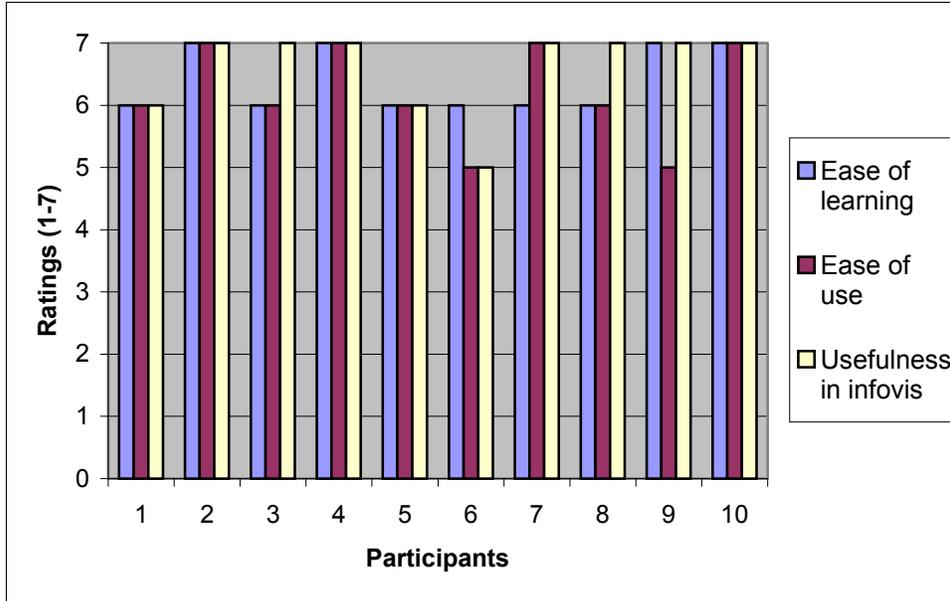


Figure 5.8 Questionnaire rating on choose from scroll list

5.2.4.3 Observations and comments

Most users learnt the scrolling technique quickly and did not have problems choosing a particular city from the list. Some users made errors by scrolling more than necessary and thus going past the desired city. However, even the users who made these errors did not express any dissatisfaction.

Since we observed these errors more in novice users than in experts, we believe that familiarity with pinch gloves might have something to do with it. Moreover, the pinch gloves we used in the experiment were large in size, and were too big for some people. This might have resulted in accidental inaccuracies while pinching and releasing the pinch.

5.2.4.4 Conclusions

Our conclusions about our implementation of the scrolling list are as follows:

“Scrolling list allows users to choose a known value easier. Our implementation of the scrolling list using pinch gloves has a low learning curve, is easy to use and provides the functionality necessary for choosing a known value.”

5.2.5 Changing attributes

Changing attributes appears to be a simple task, however is complex in fact in terms of

the number of steps needed to perform the task. The interaction with menu system for changing attributes was quite complex, since it involved multiple steps. After the user chose the ‘change attributes’ menu item, s/he had to choose a representation. The user then had to choose an attribute, or choose no attribute by choosing ‘none’ menu item. This set of subtasks had to be repeated for each attribute that was changed. In the end, the user had to pinch ‘cancel’ to go back to the default menu.

In spite of this complexity in terms of task decomposition, users found it very easy to understand the adaptation of the TULIP [BowmanTulip01]. In most of the tasks, the first action that the user performed was to change the attributes to those the task needed.

5.2.5.1 Questionnaire findings

Figure 5.8 graphically show the ratings on the ability to change attributes. All the users found it easy to understand, easy to learn and very useful in all the tasks, in spite of the complexity of the task in terms of task decomposition and the number of subtasks. The high ratings by the user for the ‘change attribute’ question in the questionnaire are particularly significant, since they exemplify how a complex task can be performed easily if the way the user decomposes the task is in synchronization with the model presented by the system and if each subtask is easy to understand. The ‘change attribute’ functionality involved a number of steps in which the individual subtask was choosing menu items from the menu. Thus the ability to perform this task was largely dependent on the ability to use the menu system. Figure 5.9 graphically represent the ratings on the overall use of menus. The users found the menu system extremely easy to use and there was almost no learning curve.

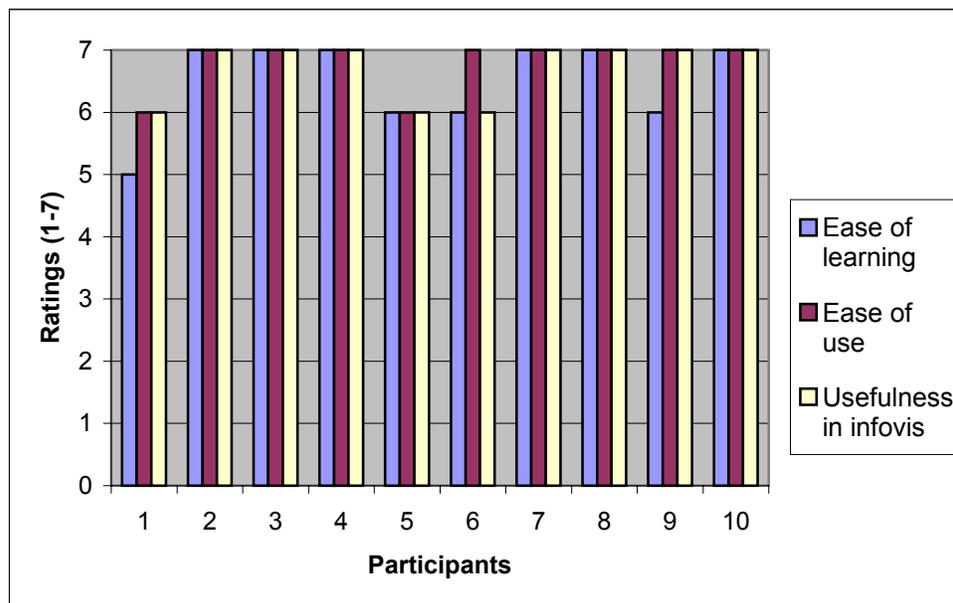


Figure 5.9 Questionnaire ratings on changing attributes

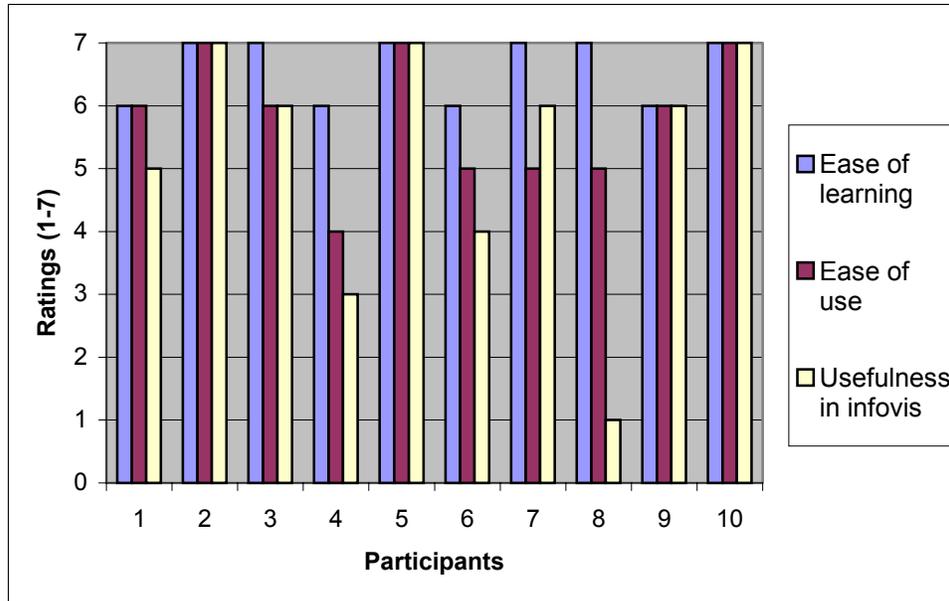


Figure 5.10 Questionnaire ratings on overall use of menu system

5.2.5.2 Observations and comments

The users were satisfied with the mechanism for changing attributes. They liked the feature where they could choose “none” as an attribute to get a two-dimensional scatter plot, which some of the people used. One interesting thing to note was the difference in the way people used the representations. Some of the tasks involved visualizing three attributes at a time. Some users preferred to view all these in 3D. Some others preferred to use 2 dimensions and color. In both cases, the users were consistent across tasks, if they used 3 spatial dimensions to visualize three attributes; they used this through out the experiment.

Most people liked the use of color, however some felt that the choice of colors (green for low and red for high) was contrary to what they expected. Most of them could make out the different color levels sufficiently for the purpose of making broad comparisons.

Almost none of the users chose to represent an attribute by size. Since there was no task that forced the user to visualize five attributes at a time, the experiment did not force the users to use size to represent an axis. Hence we cannot comment on how useful size can be as an attribute to visualize data.

There were some valid suggestions about the way the menus were implemented. One of the users felt that the transition of menus from the palm to the fingers on pressing the next button would be enhanced with some kind of feedback. One possible way would be to animate the scrolling action. Another way would be to have each “menu set” have a different background color, so that when the menu set on the fingers changed, the change would be noticed immediately. There was also a suggestion that the special menus needed to be colored differently. The user was happy that the menus for the attributes were of a different color than the menus for “next” and “cancel,” but felt that even menu items such

as “none” should have been of a different color to make it more obvious.

5.2.5.3 Conclusions

We can conclude that:

“Users find our adaptation of the menu technique easy to use. Users found it simple to change the attributes using the mechanism we implemented. Users can use three spatial dimensions and color to represent different attributes.”

5.2.6 Multi selection and zooming

Not all the users used selecting a group of points in the overview mode. None of the tasks forced the users to do a selection using the bounding box technique, and none forced the users to choose zoom.

5.2.6.1 Questionnaire findings

Figure 5.11 shows the questionnaire ratings about the ability to choose multiple points by drawing out a bounding box in the overview. The users gave the selection in the overview a close to average rating in most cases, but rated it highly on its usefulness.

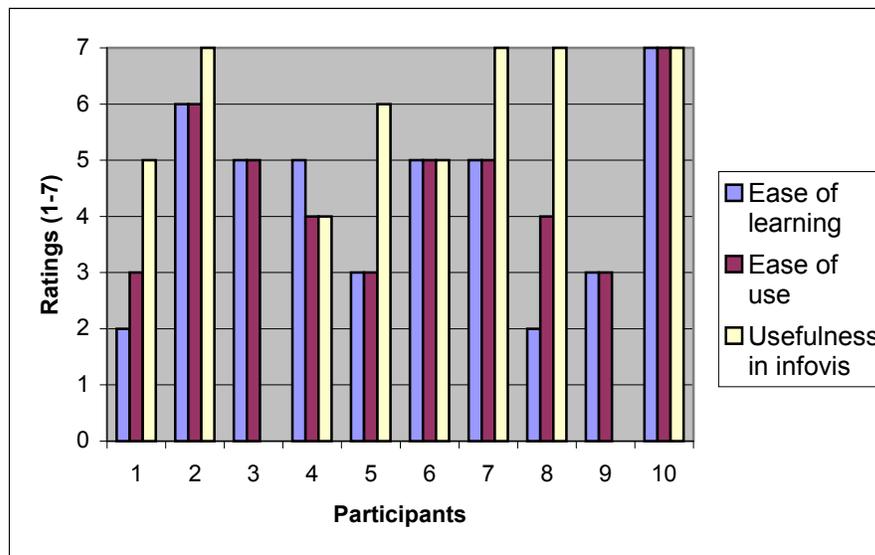


Figure 5.11 Questionnaire ratings on ability to choose multiple objects in the overview

Figure 5.12 shows their ratings about “filter data” technique to visualize a subset of the complete dataset. The blanks in the graph denote places where the user did not choose to rate the question on those criteria. The filter data is dependent on the selecting in the overview since selecting multiple objects by drawing a volume makes more sense in the overview than in the detail view.

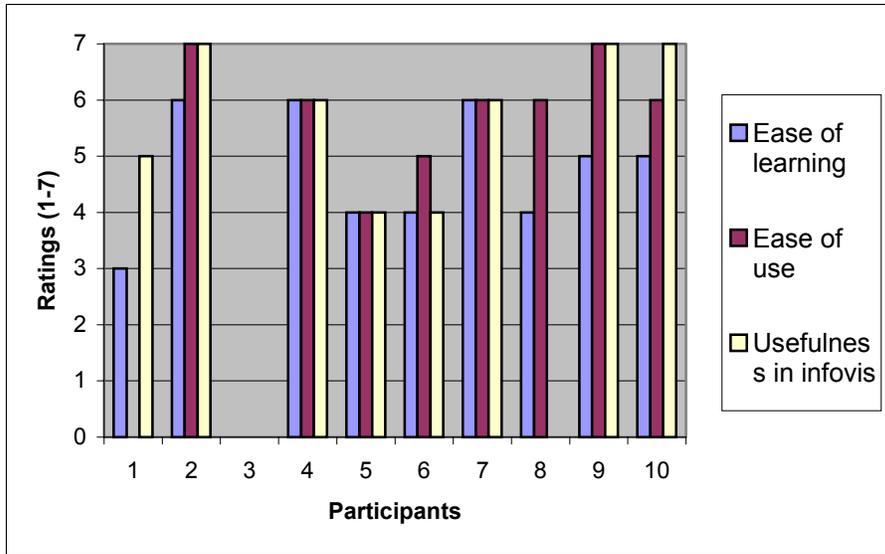


Figure 5.12 Questionnaire ratings on use of filtering data

By looking at the two graphs simultaneously, we can observe that the two graphs have an identical appearance. Since we know that the filter data follows selecting multiple points in the overview in most cases, we can conclude that that the users' ratings on "use of filter data" are dependent on their ratings of the ability to choose multiple points in the overview.

5.2.6.2 Observations and comments

In our observations we noticed some very creative uses of choosing points in the overview. People often used this to select even a very small number (one or two) of points which they could select by drawing out a volume around it, and then flag it so that they could keep track of the points, or sometimes flag it so that it gets marked and when the users jump from overview mode to the detail mode, it is easy to recognize the flagged point.

We found that power users used the filter technique on tasks that required the users to focus on a subset of data. This often helped them get a better understanding of the data. The users who used the filter data technique were satisfied by the way it was implemented. Some of them were slightly confused however, since the user who selected and filtered points in the overview mode, was suddenly put in the detail mode after the "filter data" operation. This was inconvenient and is something that should be fixed in an implementation of this technique.

Some of the users remarked that they should be able to save the results of the filter, or in general, be able to save a list of selected objects. This would save time when they had to do similar tasks.

5.2.6.3 Conclusions

We feel that

“Choosing multiple data points and filtering techniques has a potential use in infovis. Further study is needed to be able to generalize the “filter data” option using a novel query technique beyond ordinary multiple selection.”

5.2.7 Moving to origin

Moving a selected object to the origin is a very infovis specific task. Not all users used this.

5.2.7.1 Questionnaire findings

Figure 5.13 shows the users’ rating on their opinion of the ‘move to origin’ technique. The graph shows that most people rated this technique above average, and a lot of them rated it highly.

Moving a selected object to the origin is not a hard task, but a possible difficulty can be the disorientation that might be caused as a result of this action. However, users did not notice any such disorientation. First, the users expect a sudden change in the view when they choose this action. They do not get confused when the view changes because they know what has happened. Secondly, the users can use the “go to” action to go to the selected object. Thus the users could get to the origin and the point they had selected.

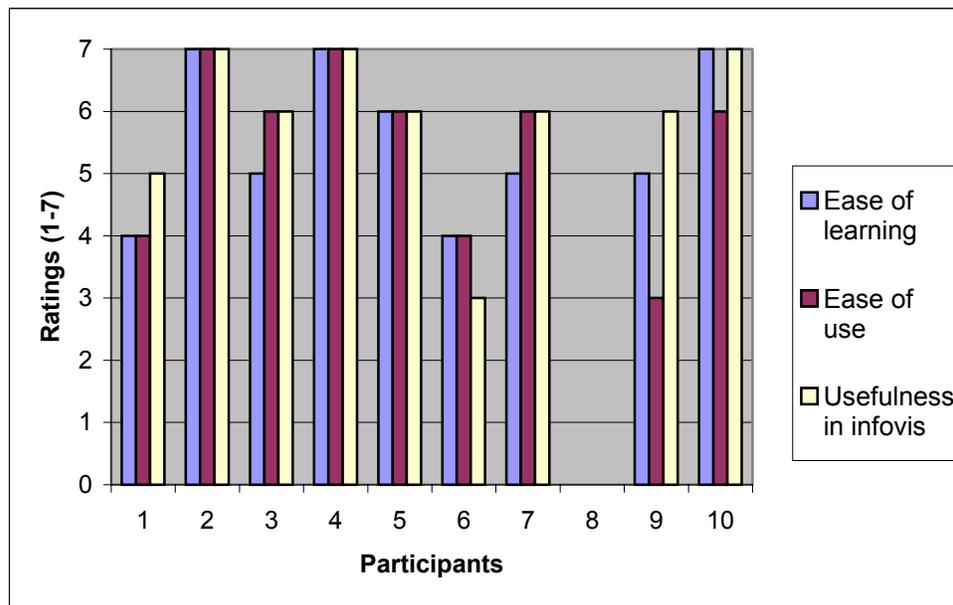


Figure 5.13 Questionnaire rating on 'move to origin' technique

5.2.7.2 Observations and comments

The users who used this feature also used it in Task 3, in which the user had to identify two cities that had certain values lower and some values greater than a particular city. The way the users did this was to identify the city, move it to origin, and then jump back to the overview. They then identified the octant in which their target cities lied, and then jumped into that octant.

While filling out the post-experiment questionnaire, some users who didn't use the "move to origin" feature in the origin remarked that they had completely forgotten about this feature, and when they saw the question in the questionnaire, they were reminded of it. They also said that they wished they had remembered to use this feature in those tasks, since they thought this would have been of use to them.

5.2.7.3 Conclusions

From this we can conclude that:

"Using the "move to origin" technique results in greater understanding while performing tasks in which we need to make comparison with a known fixed point based on certain attributes."

5.2.8 Providing help and feedback

We tried to provide some sort of feedback for every task. The simplest feedback the system offered was a 'click' sound made whenever the user pinched. Help was provided at all stages in form of context sensitive help on the tablet.

5.2.8.1 Questionnaires

Figure 5.14 shows ratings on the questionnaire for the questions on whether the system provided adequate feedback, and whether they found the help that flashed on the tablet useful.

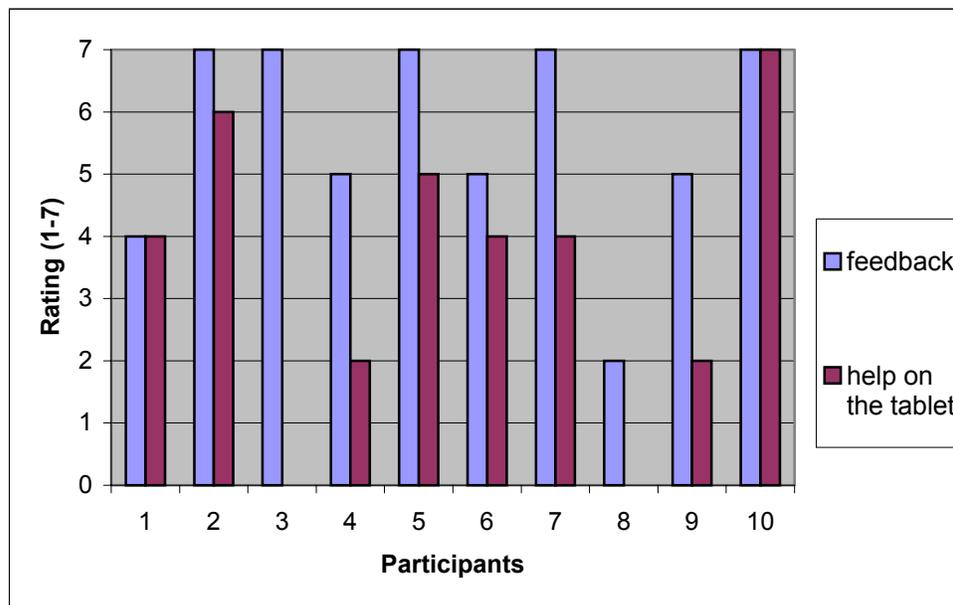


Figure 5.14 Feedback and help rating

Most users had the opinion that the visual and auditory feedback offered by the system was, to a large extent, adequate.

Most of the users did not think highly of the help offered. In the overview mode, the tablet was adjusted so that when the overview was near the user, the tablet was hidden. This was done so that the users could read the help if they needed, but when the overview was not in their view.

5.2.8.2 Observations and comments

For most users, this was an unnecessary obstruction. The training phase had equipped the users for most of the tasks. The users didn't feel any need for reading help on the tablet. Since they didn't require the help, the help that popped up on the tablet in the overview mode was occasionally a nuisance. This explains the low rating for the help.

Some users asked, "How can I get rid of the green thing (the tablet) in the corner?" Others tolerated it silently, but almost none reported using it much. Moreover, even as the users became more and more proficient in using the application, the help continued to appear.

5.2.8.3 Conclusions

This teaches us an important lesson that:

"Help should be provided only initially, and should be non-obtrusive. An adequate training phase can reduce the need for help. Help should be provided for the novices and should get out of the way of the experts. Feedback should be provided for each and every action. Use of colors, sounds enhances the feedback"

5.3 Using the complete application

In the previous section, we discussed some of the results of the experiment, particularly those specific to a particular task or interaction technique. In this section we discuss some of the ratings on the questionnaire related to the entire experiment, and the entire Wizard 2.0 application.

5.3.1 Timings & Errors

Most of the tasks involved more than one interaction technique, and hence analysis of the complete application involves analysis of the results of the experiments in terms of the timings and the errors on different tasks. While we have discussed some of the tasks in various sections before, in this section we present the analysis of the other tasks.

5.3.1.1 Analysis of Task 1 results

Task 1 involved finding two cities that met a certain criteria for three of their attributes. This is a relatively straight-forward task. None of the users had any errors on this task. Our target was for this task was 2 minutes. Although some users needed more time than that, the average for the group was 84 seconds, which met our target.

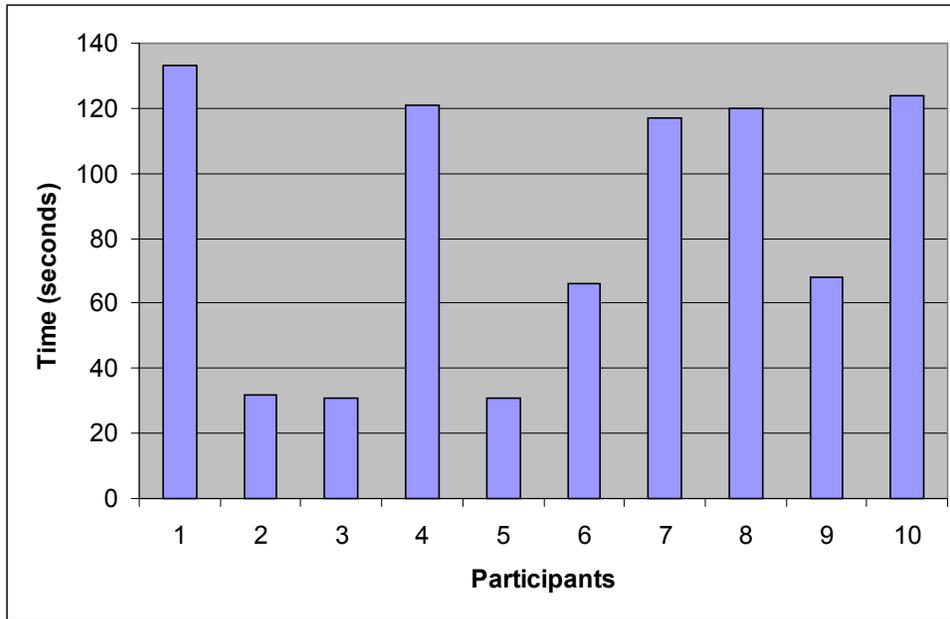


Figure 5.15 Timings on Task 1

5.3.1.2 Analysis of Task 2 Results

Task 2 was comprised of two subparts. The first part was more complex. The users had to identify two points that were similar within a certain tolerance level based on certain attributes. The second part of the task was to compare them based on some other attributes. Since this was a slightly complex task, we set a target of 2 ½ minutes.

Some of the users made minor errors while performing the comparison in the second part of the task. However, by and large, the users were able to complete both tasks successfully. The average time taken for task completion was 130 seconds, thus meeting our target.

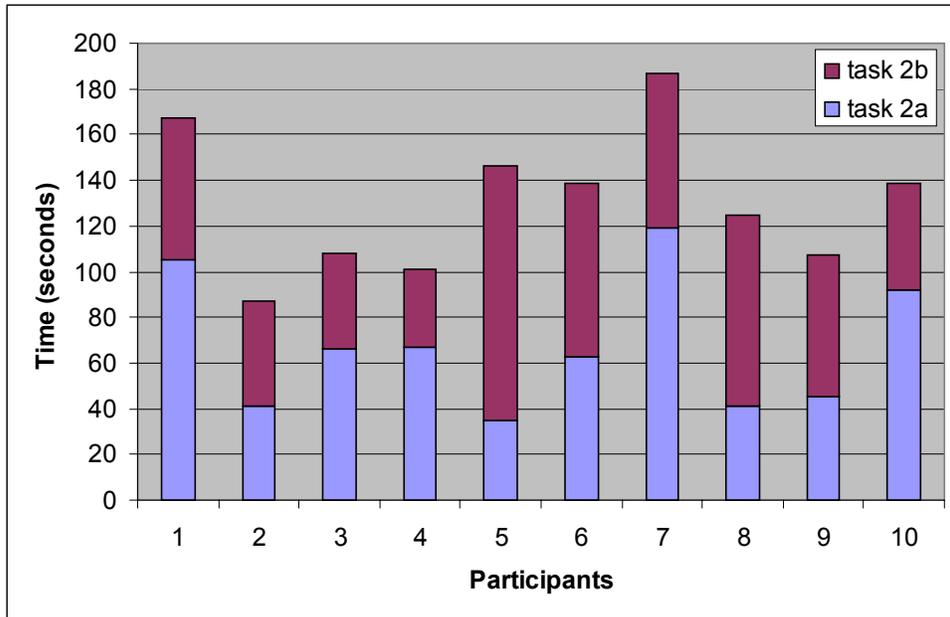


Figure 5.16 Timings on task 2

5.3.1.3 Did we achieve the targets we set?

The targets we set for the tasks were on the conservative side, considering the fact that the infovis process is largely based on exploration, and it can take different people varying times to complete the same task successfully. Based on the results of the experiment we were able to achieve the targets we had set for Tasks 1, 2, 4 and 5 for the time taken for completion as well as error rate. We were unable to meet the target we had set for the time taken for Task 3, and the error rate is not entirely to our satisfaction even though all the errors were minor errors. We attribute our failure to meet the target for Task 3 on the problems faced by the users while interacting with the detail mode.

We were able to achieve the time target set for Task 6. However, two users gave erroneous opinion on Task 6. While this may be due to personal limitations of the users in visualizing 4 attributes simultaneously, we believe that it may also have been a deficiency in our system, and cannot claim complete success for the target we set for error rate in Task 6. However, we must recognize the complexity of the task, and the target set was extremely ambitious considering the complex nature of this task, and thus we can say that the performance on Task 6 was moderately successful.

5.3.2 Questionnaire findings

Certain questions in the questionnaire were general questions about the entire experiment. Figure 5.17 is a graph showing the ratings on some of the questions about the environment.

All the users felt that the application provided all the functionality that is needed to

visualize a scatter plot. All the users gave a very high rating (6 or 7) to the question that asked if the environment provided the functionality needed for visualizing data. Since the tasks we chose represent typical tasks in infovis, we can conclude that the environment provides the functionality necessary for information visualization.

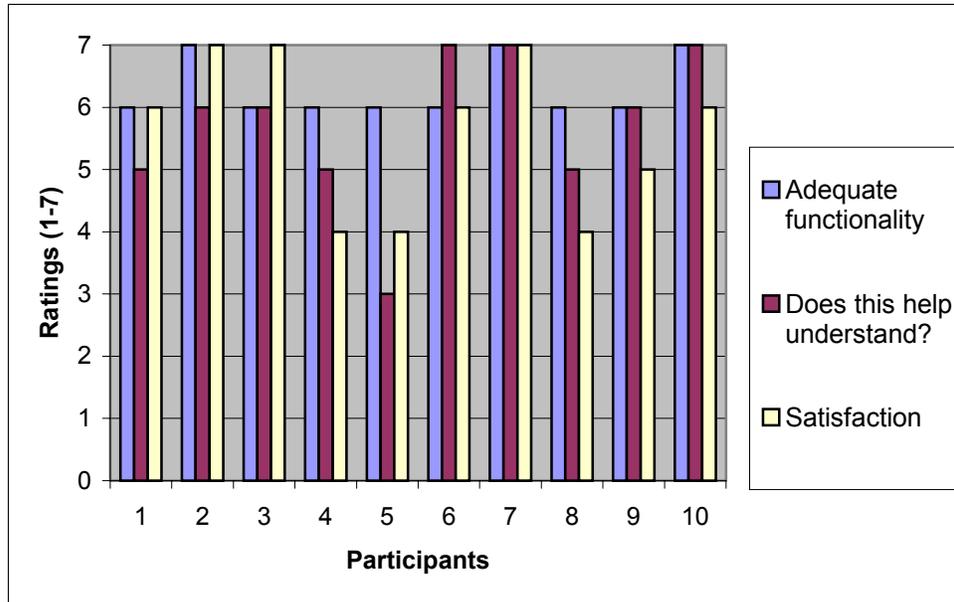


Figure 5.17 Ratings on some general questions

Most users also felt that such an environment helped them understand the data better. The ability to get multiple views and the ease of manipulation of the overview led to increased understanding of the characteristics of the dataset; the ability to change attributes and representation was also useful sometimes.

In applications like these, it is very important that the users not only perform the tasks well, but also feel satisfied with their experience. All the users rated this application above average in terms of satisfaction provided, and most of the users rated it high on satisfaction.

5.3.3 Observations and comments

While observing the users perform the experiments, the experimenters got a lot of information about the way the users perceive the environment. Particularly useful for this was the second phase of untimed tasks, which offered an opportunity to understand the thought process of the user.

Training is an important phase in applications like these. One of the users commented, “After the first two sessions, it is a piece of cake to do the tasks in the third phase”

5.3.4 Conclusions

There are some things that we can conclude as a result of this experiment. While we have already talked about specific conclusions, there were certain observations that led us to

make this conclusion:

“Users have a good ability to break down a complex task into a series of smaller subtasks. Different users often have varied ways of performing the same subtask, but eventually all of them are able to achieve the goal.”

This conclusion proves that users can use a tool that enables them to decompose a task into subtasks and then perform even seemingly complex tasks with ease.

5.4 5.4 Comfort ratings data

The comfort ratings were taken at intervals during the experiment. The four times at which the comfort rating were taken are as follows (time represents time from start of experiment):

1. After familiarization with VE equipment (approx 0:05)
2. After “learning phase” (approx. 0:50)
3. After 1st session (approx 1:15)
4. After 2nd session (approx 1:40)

The comfort ratings are based on the arm strain, hand strain, dizziness and nausea. The complete table of comfort ratings is included in appendix D.3.

5.4.1 Arm strain

The comfort rating of the arm strain that the participant noticed during the course of the experiment shows an interesting trend. Figure 5.18 shows the comfort ratings of the subjects in form of a graph.

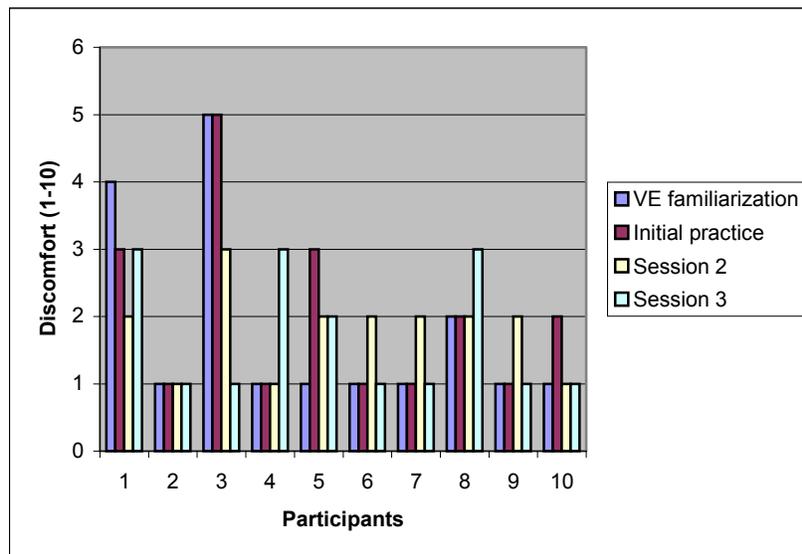


Figure 5.18 Comfort ratings for arm strain

Here we notice that for the users who had high ratings for arm strain initially, the ratings

decreased during the course of the user study. Initially the users always raised both the arms to see what's on each hand, particularly to read the different menu items on the right hand. However, once they learnt to keep the hands comfortable when not needed, eventually the users didn't need to keep both arms raised all the time. Some of the users also became adequately familiar with the menus that they could use some of the menus by pinching the right digits, even without having to read the labels of their digits. Hence as time progressed, they felt more comfortable with the pinch gloves and trackers.

Some of the comments made illustrate this point. "My arm strain reduced... since I got used to keeping the hands out of the way when not needed." Another person said, "It was better once I figured that I didn't need to look at the hands before pinching select to select the point."

5.4.2 Hand strain, dizziness and nausea

Most of the subjects felt very little hand strain. Three subjects felt a moderate amount of dizziness, and only one subject experienced moderate nausea. While the weight of the HMD contributed to general discomfort for some of the participants, the subject who felt the nausea had not focused the HMD correctly during the last phase of the experiment, which added to the discomfort.

5.5 Summary

In this chapter, we analyzed the results of the experiment. The experiment yielded results from which we could make valuable conclusions about the effectiveness of the interaction techniques we developed as well as the ability to do infovis in virtual environments.

We found out that selecting an object by touching it is intuitive. Navigation using hand-directed steering does not work well for all users. We suggested alternative ways of selection and navigation using ray casting.

We found that the infovis techniques we developed were easy to use and usable, and helped the users complete the tasks successfully. Users are able to take a complex task, decompose it into subtasks, and perform them using the functionality offered by the system.

We concluded that virtual environments provide a potential for infovis, and users are able to understand the data using these techniques and are satisfied with their experience. Interaction techniques need to be adapted for their use in virtual environments. Our implementation of the overview + detail is a successful adaptation of the infovis technique in virtual environments.

6 Experiment 2:

Experiment to determine the use of immersion for understanding information in information rich environments

Our second experiment tests the second hypothesis about the use of immersion for understanding data with spatial attributes. In this chapter, we outline an experiment to test the hypothesis. The chapter starts with a brief outline of the experiment and then describes the details about the subjects, the environment, the experimental design and the data collected.

6.1 About the experiment

6.1.1 Purpose

This experiment is to validate our hypothesis about characteristics of data that make it suitable for a particular visualization.

Our hypothesis was that if the data to be visualized has some attributes that are inherently spatial in nature, or is dependent on spatial attributes then the data can be visualized better in an immersive virtual environment than on a desktop. If we have empirical evidence that this is the case, then we can use this knowledge for more complex visualizations that involve some attributes that are inherently spatial in nature. For example, in visualization for studying fires, we can visualize a data obtained discrete event simulation in which a lot of attributes at each point such as temperature, percentage of oxygen and carbon dioxide in the air, etc, are largely dependent on spatial attributes such as size of room, distance from fire in each direction, etc.

6.1.2 Brief outline of the experiment

For our experiment, we needed some data that was dependent on, or was a function of the location of the point in space.

In this experiment, the user can move around in a large room filled with different objects, some of which are radioactive. The radioactivity at any point is inversely proportional to the distance of the probe (which the user manipulates) and the source. The user's task is to detect which of the objects in the room are radioactive.

The radioactivity is thus something that is dependent on the spatial attributes of the objects in the room, in fact is a function of the spatial location of the probe. The users task involves recognizing the dependency of radioactivity with the location and an ability to detect the changes in radioactivity by moving the probe in different directions.

6.1.3 Typical immersive and desktop environments

The two experimental setups that we use are desktops and immersive VEs.

Firstly we must acknowledge the fact that these systems have a lot of differences. Desktop technology has progressed aggressively, and a typical desktop display is a 17" or

a 19" monitor that is capable of showing millions of colors with a display resolution of 1280 X 1024. Head mounted displays, on the other hand, usually have a screen resolution of 640 X 480. Desktops have entered everyday lives of people, and people are familiar with desktop metaphors such as the WIMP. On the other hand, people are not as familiar with VEs. There is a difference in the interaction techniques on desktops and in VEs.

VEs however have advantages such as use of trackers that facilitate 3D interaction techniques. Level of immersion offered by VEs is more than the immersion offered by desktops. The benefits of immersion for task performance are the area of research in this thesis.

There is lot of grey area in terms of what constitutes a VE system; "wall" or other stereo displays can certainly be used like a desktop. Uses of devices such as cubic mice facilitate 3D input on desktops.

Our intention is to study whether immersion affects task performance. The inherent problem in this is the tradeoff in evaluating real systems, where results can be easily applied to the systems currently in use in real life, but there are a lot of confounding factors, and it is hard to identify whether the effect observed is due to an individual factor, or is a combined effect of several factors. Contrary to this, by evaluating carefully controlled situations, it is easy to see what factors influenced the results. However, this makes the experiment hard to apply to real systems.

In our experiment, we chose the real system approach. We compared a 'typical' desktop with a 'typical VE'. 'Typical' desktop refers to a typical computer with a monitor for output, using a keyboard and mouse as input devices. There is a large variety in display devices and input devices for VEs, but typical VEs consist of some 3D display device that surrounds the user, such as head mounted displays or spatially immersed displays. Although it is not a requirement for virtual environments, most immersive environments have some sort of 3D input device, such as a stylus or wand or trackers. The 'typical' VE refers to a HMD based setup, with head and hand tracking, using a wand as an input device.

The advantage of this choice is that the results of the experiment can be directly applied to real systems. This is a more practical approach, and it is easy to use this for making design decisions while building applications for typical systems. On the other hand, since we have not controlled all the variables in the setup, we cannot identify the exact factors that influenced the results. We could do this by using a wand as an input device on the desktop as well. While this would have controlled the factors that influenced the results, it would not be very useful in real world, since typical desktop systems do not use wands.

In our experiment, the screen resolution could possibly impact the performance. We decided to use the same resolution on the desktop and in the VEs. The difference in the navigation techniques could be a factor in the task performance. This could seriously hamper the usefulness of this experiment. To avoid this situation, we implemented identical navigation techniques in the VE and on the desktop. The user was given training

and practice until s/he reached a certain level of comfort in both the environments. We believe that adequate training can compensate for the difference in the two navigation techniques and thus not heavily influence the results.

6.2 Method

6.2.1 Subjects

The user study to test the effect of spatial characteristics involved 16 users. The users were unpaid volunteers. The users were of varied age groups, the youngest was 16 years, and the oldest subject was 55. There were 10 males and 6 females. 7 of the subjects had very little, or no previous experience with VEs. 10 subjects had very little exposure to 3D computer games, while 6 subjects had a fair amount of gaming skills. We wanted to know if these conditions affected the user performance.

6.2.2 Apparatus and implementation



Figure 6.1 Equipment used in the 2nd experiment - HMD for display, wand as an input device

The HMD in the experiment was the Virtual Research V8. It supports a resolution of 640x480, with a sixty-degree diagonal field of view. The HMD presented biocular images to the user. We used Intersense IS900 tracking system to track the head and right hand of the user. On the right hand, we used a wand device that also had a joystick. The application was developed using the SVE toolkit [Kessler00] and ran on a PC that was also used for the user studies on the desktop.

The PC was a 1.6 GHz Pentium with 520 MB RAM and a graphics card with NVidia

GeForce2 chip and 64MB memory on board.

6.2.3 Environment

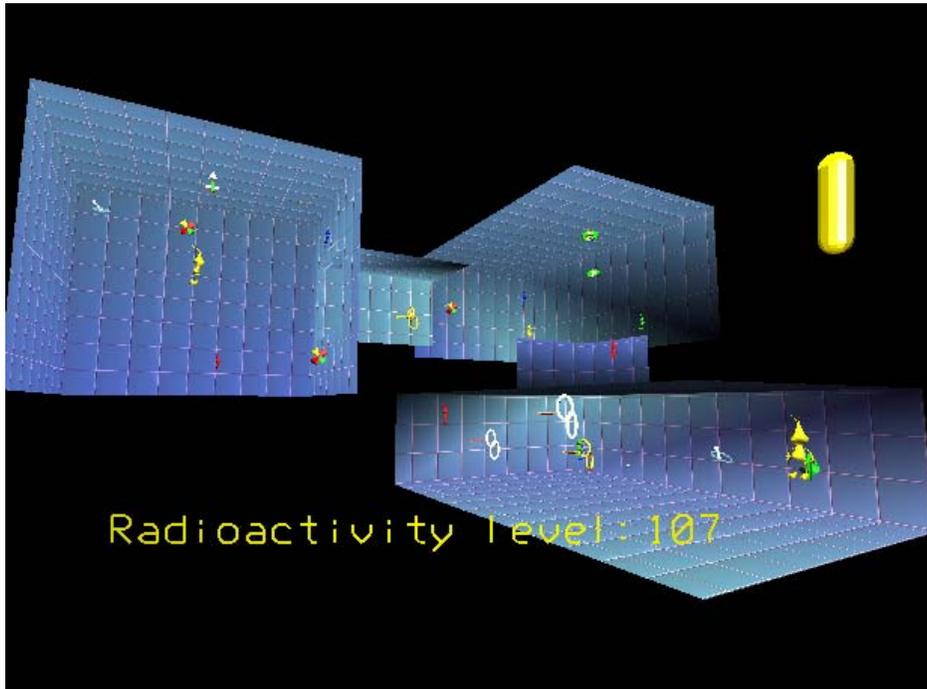


Figure 6.2 A view of the submarine from outside the submarine. The submarine essentially consists of three chambers that are connected by corridors.

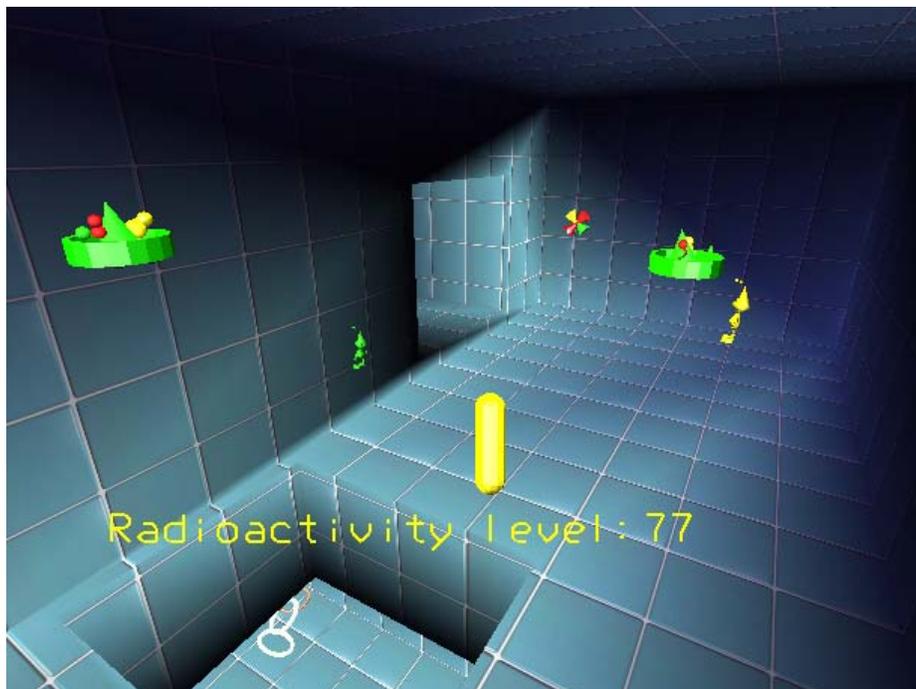


Figure 6.3 This is what the inside of the submarine looks like. The user views only the inside of the submarine for all the tasks.

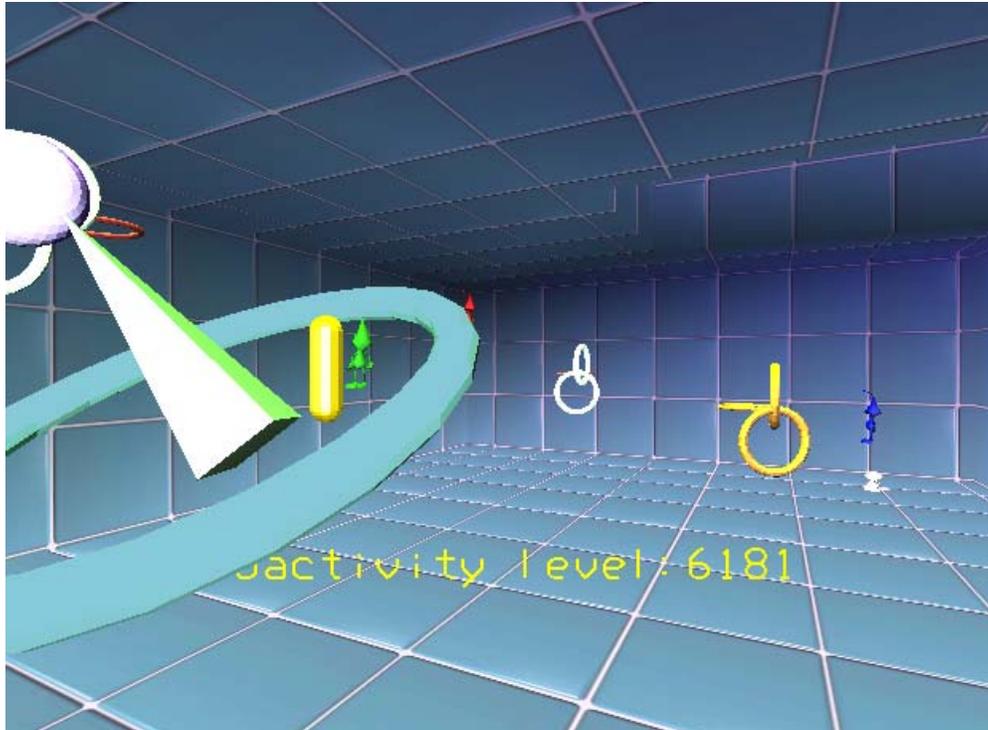


Figure 6.4 As the probe moves closer to the source of radiation, the radioactivity level rises rapidly

The environment is “submarine station”, which is a complex shaped house that consists of some rooms and corridors. Some rooms have some multi-level partitions and platforms. The submarine has lots of different objects scattered all over at any time. Some of these would be “radioactive”.

The wand acts as the “radioactivity probe” and detects radioactivity that is a function of the wand’s distance from the source. The radioactivity at any point, as well as the x, y and z coordinates of the user are displayed on a display that is constantly visible. The radioactivity is inversely proportional to the distance of the wand from each source. The sources may be positive or negative in nature, and opposite sources may cancel effect.

6.2.4 Interaction Techniques

For navigating through the submarine, we could either use gaze directed steering or hand directed steering (pointing). We preferred to use gaze directed steering since “there is a more direct feedback loop between the sensory device (the eyes) and the steering device (the head)” [BowmanTravel97]. Another reason for using gaze directed steering is that we can implement identical techniques on the desktop on which the user can use cursor keys to move in the direction s/he is facing instead of using the joystick. Either way, the user moves forward, backward or sideways with reference to the direction s/he is looking at.

While using the immersive VE, the user can choose to go faster or slower by selecting the buttons on the wand. The joystick is used to move forward, backward and to strafe

sideways. While using the desktop system, the user can use keys ‘a’ to accelerate and ‘s’ to slow down. The user can use cursor keys to move forward, backward and strafe sideways. The user can also use the right mouse button to move forward in the direction of gaze.

In order to change the direction in immersive VEs, the user simply turns his body, or rotates his head. This rotation comes naturally. For the desktop application, the user can click on any part of the screen and then drag the mouse in the direction s/he wants to turn.

In the VE experiment, the users can use the wand to manipulate the “probe” that detects radioactivity. The radioactivity value is always displayed in front of the user, and is the value at the point where the probe lies. For the application on the desktop, the probe is at a constant offset in front of the user. The user can however manipulate it two-dimensionally by using the mouse; the probe moves when the user moves the mouse around. We thus give the user two degrees of freedom to manipulate the probe since we use only a mouse, which is a 2 dimensional input device.

We attempted to have similar interaction techniques in both applications. Moreover, prior to the timed trials, the users were given adequate opportunities to use all the interaction techniques. These practice sessions lasted as long as the user showed a sufficient level of competency in using either techniques. We feel that with adequate training it isn’t a confounding factor that the two conditions use different interaction techniques.

6.2.5 Experimental Design

We used a within-subjects design, in which all the users did the trials in both conditions (desktop and VE). Both sessions were conducted at the same time, one after the other. The order of sessions was alternated; half of the subjects started with the HMD first, and the other half started with the desktop first. The independent variable was the condition itself in terms of the display device (VE using HMD against desktop). As explained in the previous section, interaction techniques were not independent variables. The dependent variables were time for completion of task (measured in seconds) and number of errors (false positives, or incorrect answers).

In each of the two sessions, there were 4 trials. The users used identical trials in both conditions. Each user had a unique sequence of the trials. Each trial had two objects that were radioactive sources. The user could “sense” the radioactivity at any point using the probe. The tasks involved finding the sources of radioactivity in the submarine.

At the end of each set in the session, we asked questions regarding the user’s level of comfort at that time. They were asked to give a rating between 1 and 10 to assess their level of arm strain, hand strain, dizziness, and/or nausea.

6.2.6 Procedure

After reading and signing the informed consent form, the volunteers were asked to fill in the pre-experiment questionnaire that contained demographic information such as age,

gender, and occupation (or major field of study), and for information on the subject's knowledge of computers and prior experience with VEs. After that they were asked to go through the instruction sheet, and then those unfamiliar with the VE equipment were told about the basic setup and hardware.

In each case, the task was to move around in the room and identify the "radioactive sources." There were three timed trials within each setup. After the subjects were done using one display device, they performed identical tasks using the other display. The time was measured as soon as the experimenter said "Go" at the start of a task, until all the sources were successfully identified. False positives, or objects that were incorrectly identified as to be the sources, were noted as errors, and the users were asked to continue investigations.

At the end of the experiment, the users were asked to participate in a brief interview session. During this interview, they were encouraged to make comments or suggestions, or ask questions they had about the system, techniques, or devices.

6.2.7 Data collected

Objectively, we measured the time for completion of the task for each trial. The time taken to complete the task is a measure of efficiency with which the user is able to perform a task. With a greater understanding of the relationship of the value of radioactivity with the spatial location, the user would be able to perform the task faster.

We also measured the number of errors made. In our experiment, we had no conditions in which one object was at the same position as another. Hence, if the user chose an incorrect object, it meant that the user was unable to adequately understand the space around him.

We measured the comfort level from time to time, and also got objective data on the user's satisfaction, when performing the tasks.

The subjective data was collected by observing the user perform the task and by taking notes during the tests. The tests were audio-recorded to facilitate transcription, but the experimenter also made notes during the experiment. Critical incidents that occurred during the evaluations were noted, and users' oral comments and feedback were recorded; some of the salient comments are listed in section 7.3.

6.3 Conclusion

In this chapter, we first outlined the experiment, and then specified details about the experiments such as: subjects involved, environment, experimental design and data collected. In the subsequent chapter, we present the results of the experiment and our analysis of the results.

7 Analysis of results of experiment 2

The previous chapter discussed the experimental setup and method for the second experiment. In this chapter we discuss the results of the experiment. We discuss the outcome of the experiment not only in terms of the time required for tasks, but also based on the observations and interview. The observations made by the experimenters during the experiment are also recorded and are important for this analysis. We also mention comments that the subjects made during the experiment.

We draw inferences based on all this data, and support these based on some of the results.

7.1 Basics

Drawing conclusions on the results of an experiment is based on a careful analysis of the data obtained from the experiment. Here, we present some data to support our inferences. The data we used was obtained from a number of sources, timings, interview, etc.

7.1.1 Pre-experiment questionnaire

The pre-experiment questionnaire (see Appendix C.1) was more of a demographic survey. Points of specific importance to us were the answers on previous experience with VEs, and previous exposure to 3D games. The users rated their knowledge on a scale of 1 to 5, where 1 meant no experience and 5 meant expert users.

7.1.2 Timings & Errors

The experimenter recorded the timings and errors. The timing started when the experimenter said, “Go” and was recorded until the subject had successfully identified both the objects. If the subject identified an incorrect object, it was recorded as an error, a false positive.

7.1.3 Post-experiment interview

In the post experiment interview (see appendix C.3), the experimenter asked the subjects about their opinion of the two environments and their ability to use and understand the environments.

7.2 Task performance

The task performance was evaluated based on two criteria, time taken to complete the task and number of errors.

7.2.1 Timings

Figure 7.1 shows the mean time taken for task completion for subjects. For this, we determined the mean based on the results of the 4 trials. We notice from the graph that the timings show a large variation. Appendix E.1 contains a table showing the timings for individual trials, as well as the mean and variance for each subject under each condition.

11 out of 16 subjects completed the tasks successfully in the VE quicker than they did on the desktop. The average time taken for task completion in the VE is 90.5 seconds, whereas the average time for task completion on the desktop is 107.4 seconds. There

seems to be a trend that the task performance might be due to increased immersion.

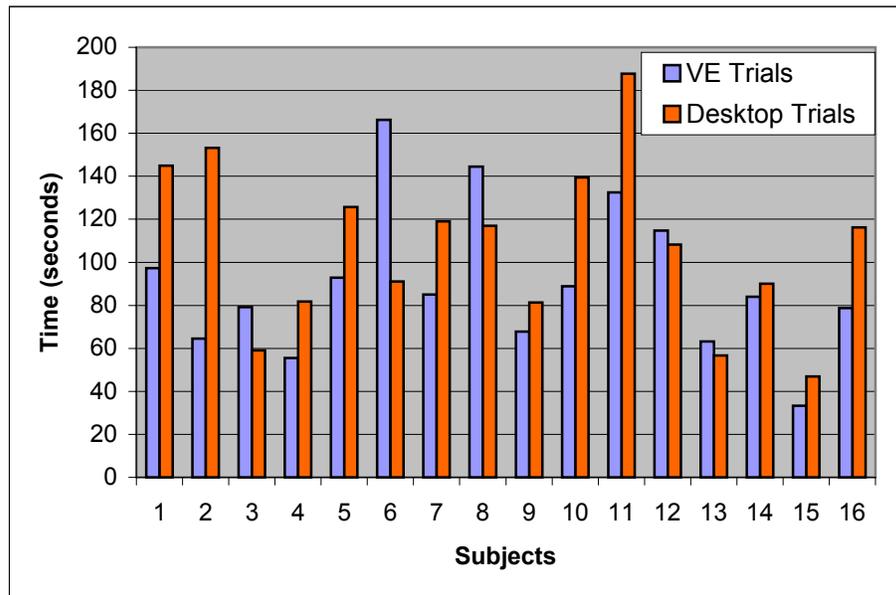


Figure 7.1 Mean time taken for completion of tasks by different subjects

7.2.2 Statistical analysis of time

For statistical evaluation, we used all the timing data obtained from the experiment. We chose to perform a more complete analysis of variance (ANOVA) with the data from all the trials, rather than a simplified ANOVA using only the means of the trials.

7.2.2.1 Design of experiment

Before we go into the details of the statistical analysis, let us recapture the experimental design. We had 16 subjects who participated in a within design experiment in which each user completed 4 trials under each of the two conditions (Desktop, VE). This is a within-subjects design in which each subject completed 8 trials (4 trials under two distinct conditions). The design then is a 2 (condition) x 4 (Trials) within-subjects design. [Ollendick 02]

7.2.2.2 Statistical model

This is a completely randomized design (CRD) with sub-sampling, where the two conditions are treatment (T), user is experimental unit (EE) and individual trial is observational unit (OU) [Hinkelmann 94]. The model is [Zhong 02]:

$$SS(T) = \sum_i \sum_j \sum_k (\bar{y}_{i..} - \bar{y}_{...})^2$$

$$SS(EE) = \sum_i \sum_j \sum_k (\bar{y}_{ij.} - \bar{y}_{i..})^2$$

$$SS(OE) = \sum_i \sum_j \sum_k (\bar{y}_{ijk} - \bar{y}_{ij.})^2$$

$$SSY = \sum_i \sum_j \sum_k (\bar{y}_{ijk} - \bar{y}_{...})^2$$

F-value of treatments can be computed using the formula

F-value = MS (T)/MS (EE).

7.2.2.3 ANOVA

ANOVA table for CRD with sub-sampling is as follows: [Hinkelmann 94]

Source	d.f.	SS	MS	F
Treatments	t-1	SS(T)	MS(T)	MS(T)/MS(EE)
Experimental Error	T(r-1)	SS(EE)	MS(EE)	MS(EE)/MS(OE)
Observational Error	Tr(n-1)	SS(OE)	MS(OE)	
Total	Trn-1	SSY		

Using SAS we get the following results for ANOVA on the data: [Zhong 02]:

Source	d.f.	SS	MS	F	p-value
Conditions	1	9146.281250	9146.281250	2.73	0.1089
Users(Conditions)	30	100507.4375	3350.2479	1.55	0.0571
Error	96	207528.0000	2161.7500		
Total	127	317181.7188			

Analysis of variance reports the p-value to be 0.1, which is greater than 0.05. Thus the results are not statistically significant.

7.2.3 Errors

Figure 7.2 shows the errors made by the users during the trials. In general, the subjects made few errors. When the subject did make an error, s/he was able to recover almost immediately and identify the correct object that was usually some other object in the vicinity of the object. Only once during the entire experiment did the user make two errors. The number of errors is slightly more in the desktop than the VE. However, analysis of variance showed that the difference was not statistically significant.

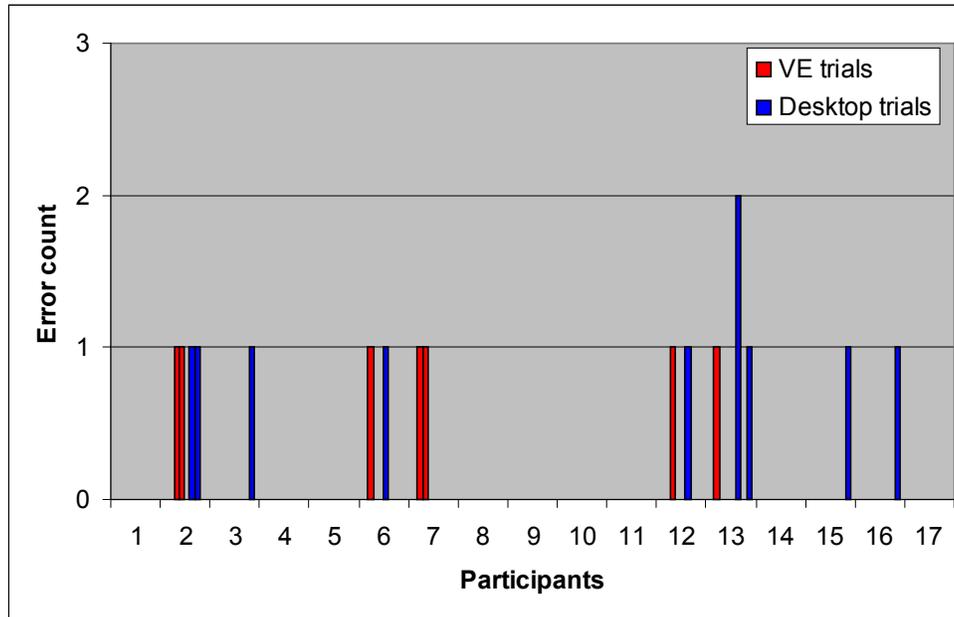


Figure 7.2 Errors made by the subjects during different trials

From this we can conclude that the immersive as well as the desktop environments allow the user to perform the task successfully.

7.2.4 Statistical analysis of errors

For statistical analysis of the error count, we cannot use the same analysis method as the first. The response only has 3 levels; error count for a trial was 0, 1 or 2. In fact, in most cases the error count was 0, and only once was the error count 2. Hence it is not a good Poisson distribution.

The statistical analysis using the GENMOD procedure (see appendix E), gives us the following results

Table 1 Statistical analysis of error count

LR Statistics For Type 3 Analysis			
Source	DF	Chi-square	Pr > Chi Square
cdt	1	0.22	0.6379
user	1	0.77	0.3792
trial	1	0.83	0.3621

We find that the results are not statistically significant. This analysis is however not as strong since the model is not accurate due to the low power of the experiment.

7.2.5 Correlations

Table 1 shows the correlation analysis. We were interested to finding out if the performance was influenced by any other factors.

Table 2 Correlations

Co-relations	<i>participant</i>	<i>gender</i>	<i>VE exposure</i>	<i>games</i>	<i>VE timing</i>	<i>desktop timing</i>
participant	1					
gender	0.3361	1				
VE exposure	0.1789	0.2878	1			
games	0.4444	0.6262	0.5630	1		
VE timing	-0.1304	-0.4485	-0.5919	-0.5908	1	
desktop timing	-0.2388	-0.3301	-0.5654	-0.6196	0.4299	1

We were interested in how these factors affected the timing on the desktop and in VEs. We notice that both previous exposures to VEs as well as experience with 3D games might be correlated to the performance. The numbers representing this correlation are highlighted in Table 1. The negative sign indicates the direction of correlation, which means that for example, as the exposure to VE increases, the timing decreases.

The correlations we noticed are not surprising. The strongest correlation we noticed is between the time taken for performing the tasks on a desktop and the previous exposure to 3D games. This is hardly surprising since a trial was similar to a 3D game. Both previous VE exposure and previous experience with 3D games have an almost identical correlation with the performance in VEs.

Some people have better spatial abilities than others. Previous experience with VEs or 3D games improves the spatial abilities of people. It will be interesting to see if immersion helps the people with better spatial abilities, to understand better even very complex spaces.

7.3 Observations made by the experimenter

During the experiment the experimenter made observations about the way the subjects interacted with the system. Some of the comments made by the subjects in between trials were recorded. The experimenter also asked questions in an interview at the end of all trials.

During the experiment, the users used a lot of natural movements. Some users used the wand to manipulate the probe around them to understand the direction of the radioactivity. HMD users often used a lot of natural motion to look around. They also used the wand to manipulate the probe, although some of the subjects seldom moved the probe. One of the corridors between the two chambers was placed in the ceiling of one chamber, and thus needed the subjects to move vertically. Only one subject found this uncomfortable.

In the interview, the subjects were asked which environment they thought they performed better in. They were asked if they felt more spatially oriented in one condition versus the other. They were also asked if they felt spatially disoriented, or “lost”, in any of the conditions.

The users’ responses are given in appendix E. We find that the users had mixed responses; most users felt oriented in both the environments, and others felt slightly more oriented in one versus the other. Two subjects had a firm belief that they were more oriented in the desktop, and three subjects felt that the VE helped them get more oriented.

Subjects who felt more oriented in the VE commented that they “ (I) felt inside, as against looking into the room from outside.” They felt that the room was around them, unlike in the desktop where they felt they were looking at a room from a window. One subject comments that “(VR) is obviously better. You have an idea exactly where you are. In the desktop you only see some area in the front. You cannot look around”.

When we asked the subjects who preferred the desktop the reasons for their choice, they felt that “It’s like playing descent”. [Descent]. We think that people who have a lot of experience playing 3D games gets them trained in using the desktop for 3D interaction.

In the interview, we asked them if they understood the way in which the chambers were connected, and we found that almost all of them had a very clear understanding of the topography. This implies that people understood the space well. We think that the environments may have been too simple for them to need immersion. It will be interesting to see if the performance differs more significantly if the environments themselves are made more complex.

To make the experiment more complex, we can have more chambers in the model, connected by structures that are slightly tricky to understand. Corridors that connect two chambers can be placed at odd angles instead of right angle. They can be made circular. The chambers themselves can be more complex in terms of more objects, objects that occlude others. One possibility may be to hide the objects altogether until the subject probes close enough to the object. Doing this will prevent the subjects from the brute force approach of testing each object in the room for radioactivity.

7.4 Conclusions

In this chapter, we analyzed the results of the 2nd experiment.

Although the results of the experiment did not have statistical significance, we can see that more subjects performed better in terms of time taken for task completion as well as number of errors made in VEs than they did on the desktop. This in itself is important, since it suggests that the hypothesis might be valid, even if the results of this experiment did not prove it significant.

The lack of statistical significance could be because of the low power of the experiment (the number of subjects was small, a more thorough experiment with a population of around 35-60 subjects would have sufficient power for ANOVA). It is likely from the trend we observed, that immersion can have an impact on task performance, and this trend needs to be explored by more experiments. Particularly, it beseeches us to explore the effect of immersion on task performance for experienced users, or users who have a higher innate levels of spatial understanding, perhaps due to experience with 3D games.

The effect of immersion on users' understanding the spatial attributes can be explored in greater depths using more experiments. One of the simplest extensions to our work is an experiment with a larger number of subjects. A larger sample population will increase the power of the experiment. A more complex environment may show greater differences in understanding under the two conditions. Similarly, a more complex task may also show such differences.

8 Conclusions and future work

This thesis is a part of an initiative to explore the possible use of immersive virtual environments for information visualization.

In this chapter, we wrap up all that we learnt from the experiment, and present two general conclusions to the questions we hypothesized. While conclusions of the two experiments are presented in the previous chapters, we recapitulate some of the more important ones. We present our contribution to this field. We suggest directions for future work that came out as a result of our experiment.

8.1 Testing the hypothesis

In the first chapter, we mentioned the problem statement and put forth two hypotheses.

Our first hypothesis was: For a better understanding and interaction with the visualization, VE-specific interaction techniques should borrow from, but not copy existing 2D IT technique for overview +detail.

Adapting, rather than adopting infovis techniques in virtual environments allows successful infovis. Our adaptation of the overview +detail technique is successful for visualizing abstract information in virtual environments. With an initial training, users find the two modes of interaction easy to use and useful for performing infovis tasks. Users quickly form a mental model of the way the two modes are related efficiently.

Our second hypothesis was: If the data to be visualized has inherent spatial attributes, then it can be visualized well in immersive virtual environments.

Our experiment shows that performance in immersive virtual environment was better than that on a desktop even though the results were not statistically significant. It indicates trends in that direction, and motivates us for further research in that area.

8.2 Conclusions of the experiments

In this section, we run through some of the more important conclusions of the experiment.

In our first experiment, overall, we found our adaptation of the overview +detail technique successful for infovis in VEs. We found out that direct manipulation of the overview provides low learning curve and high ease of use. This leads to increased understanding of the dataset, and an ability to visualize and comprehend the entire dataset.

Selecting an object by touching it is very intuitive. While our implementation of detail mode works for some users, it is not easy to use for all. Ray casting techniques offer a potential solution for some of the problems the users faced in the detail mode.

Our implementation of techniques for infovis (changing attributes visualized, moving a selected point to origin, selecting multiple points and filtering data based on selection) is also easy to use for most subjects. Together, these interaction techniques provide a rich set of functionality that allows users to perform complex infovis tasks in VEs. Use of pinch gloves for the menus and for the scroll list facilitates easy interaction techniques for input.

In the second experiment we found that the more people performed better in the immersive environment as against the non-immersive environment. We also found that previous exposure to VEs, as well as experience with 3D games has an impact on the performance for tasks that are related to visualizing data that depends on spatial attributes.

8.3 Two approaches

This thesis had two different experiments that were related to two different sides of the study of use of immersion for VEs. One of the experiments was related to abstract data visualization in an immersive VE. The other one was motivated by the need for enhancing a realistic VE with additional data.

Both of these are useful infovis techniques. The former explores a new way of visualizing information using immersive VEs. This could be useful for information analysts. The later enhances an existing VE with more information. It provides a way of getting more information in a VE without having to break the presence. This can lead to more successful applications developed in VEs for a wide range of tasks.

VEs are already being used to develop applications for architectural walkthroughs and similar applications where increased realism is desired. Supplementing this with additional information will make them more useful without much of an overhead in terms of effort required to develop such applications. We believe that this area of research can be applied immediately to the applications currently being developed. On the other hand, there is a lot of use for immersive VEs for abstract infovis, and we aspire of creating an elaborate set of information visualization tools for infovis.

8.4 Our contribution

In addition to the conclusions, we have the following contributions:

An explanation was given why immersion can be beneficial for infovis applications

In chapter 1 and 2, we explained how VE has the potentials to benefit infovis tasks, and why it is useful to exploit these benefits. The case studies we present in section 1.4 are excellent examples of applications that could benefit from this research.

We developed new interaction techniques

In chapter 3, we outlined the different interaction techniques we developed. The most important was our implementation of the overview + detail concept for visualizing a 3-D scatter plot of abstract data. We iterated this implementation to come up with one that was intuitive and easy. Some other minor novel techniques were a menu system that was a one-handed adaptation of TULIP menu system, and the implementation of the scrolling list. We evaluated the usability of all the techniques.

We introduced the Jump technique

Our implementation of the jump to change modes from overview mode to detail mode and vice versa (see section 3.5.4) is a novel interaction technique. The jump technique is important for interaction in the two modes in this environment, and has been shown to be easy to learn, easy to use, effective, and useful in infovis. (See section 5.2.3)

Wizard, an application for infovis

Wizard is the test-bed application we developed to test the various interaction techniques. Although it is currently being used to explore a fixed dataset, with slight modifications, it can be made flexible to load any dataset and allow user to visualize the dataset of his/her choice.

We studied the effect of immersion for understanding data that was dependent on its spatial attributes.

We identified the characteristics of data that make it suitable for a particular visualization. We found out that there was a correlation between previous exposure to VE or experience with 3D games, and an ability to understand data that was dependent on its spatial attributes.

8.5 Future work

During the course of this research and experimentation, we noticed interesting areas that are relevant to this work, but beyond the scope of this thesis

Use of ray casting for navigation and selection

In section 5.2.3, we saw the possible advantages that ray casting offered for some of the problems the users had with the detail view. There are a different ways to implement ray casting, and these can be studied to adapt the one that suits the purpose the best.

Adapting more infovis techniques to VEs

There are other concepts in infovis that can be adapted for their use in VEs. Particularly important to the type of infovis we are interested in are more elaborate querying techniques. Querying functionality allows the users to filter the data; this effect can be achieved by something similar to slider bars on desktop. More elaborate research is required to allow the user to specify complex queries based on Boolean expressions, negations etc.

Comparison of O+D with single view approach

It is useful to determine how much more beneficial the Overview + Detail approach is over a single view approach. Comparative experiments that measure the task performance for similar tasks using overview only, using detail only and using the O+D approach will help quantify the scale with which the O+D approach is more useful than conventional single view approaches.

Studying the effect of immersion on understanding data that has spatial attributes using more complex models and/or tasks

One way to find out if immersion helps the people in understanding data that has spatial attributes is to run the experiment again with a larger number of subjects. This will increase the power of the experiment.

Another possible initiative will be to run a similar experiment using an environment that is more complex than the simple environment we chose. Having different chambers that are interconnected in an unconventional way such as circular corridors can increase complexity of the environment. The tasks themselves can be made more complex if the number of sources varies. It will be interesting to see if immersion helps spatial understanding differently for more complex environments.

Appendix A – VE Hardware and Software

A.1 Hardware

Virtual Research's V8 Head Mounted Display

The user wears a Virtual Research's V8 Head Mounted Display (HMD), which can be adjusted by three dials for comfort and clear vision. The HMD has a 640x480 resolution with a 60° field of view. In our experiment we did not utilize its ability to do stereo or use the headphones provided on the HMD for audio.

<http://www.virtualresearch.com/products/v8.htm>

Polhemus's 3Space Fastrak

Polhemus's 3Space Fastrak is a magnetic six-dimensional tracking system, which tracked the three trackers we needed. It was used to track both of the user's hands and their head. The user was told to stand close to the transmitter, since the tracker has a limited range and is accurate within approximately 4 feet. The area in front of that transmitter was tracked.

<http://www.polhemus.com/frakds.htm>

Intersense IS 900

Intersense IS 900 is a hybrid inertial and ultrasonic tracker which is mounted on the ceiling. This allows the users to cover a wider area to move in, and provides better accuracy and less jitter. It also provides MiniTrax devices which are smaller and lighter than their counterparts.

<http://www.isense.com/products/prec/is900/index.htm>

Fakespace's Pinch Gloves

Fakespace's Pinch Gloves are a pair of gloves with magnetic material on the tips and back of the fingers and thumb. Contact between any two or more fingers completes a conductive path, and the computer can figure out which digits were pinched. In these experiments, the pinch gloves were also tracked with a Polhemus tracker so that the user's hand location was known by the system.

<http://www.fakespacelabs.com/products/pinch.html>

A.2 Soft wares & Libraries

Simple Virtual Environments

The Simple Virtual Environment (SVE) library, developed at Georgia Tech, provides a system within which a virtual environment application can be easily developed. It provides a mechanism for writing programs, and a set of functions that can be used. The programs and the library itself are written in C.

<http://www.cc.gatech.edu/gvu/virtual/SVE/SVE.html>

3D Studio Max & Wavefront Obj plugin

3D studio Max is a 3D modeling package. We used it to create most of the 3D objects used. The plugin was used to export these models in a format that the SVE library uses.

<http://www.discreet.com/products/3dsmax/>

<http://www.habware.at/duck3.htm>

Appendix B – Forms used in Experiment 1

B.1 Pre-experiment questionnaire

The pre-experiment questionnaire was used to capture demographic information of the user, as well as the user's familiarity with virtual environments, as well as their previous experience with infovis concepts and applications.

Please help us to categorize our user population by completing the following items.

Gender (circle one): Male Female

Age: _____

Do you wear glasses or contact lenses (circle one)?
No Glasses Contact Lenses

Occupation (if student, indicate graduate or undergraduate):

Major / Area of specialization (if student):

Rate your familiarity with Virtual Environments: (circle one)

•-----•-----•-----•-----•-----•-----•
none very little some VE experience lot of VE exposure
experienced in VEs

Have you ever used a virtual reality (VR) system? If so, please describe it (what type of display was used, what kind of application (e.g. game, architectural walk-through) was running, how did you interact with the system, etc.).

Rate your familiarity with Information Visualization: (circle one)

•-----•-----•-----•-----•-----•-----•
none very little some experience lot exposure
experienced in infovis

Are you acquainted with information visualization concepts? Have you used any tools such as Graphs in Excel? Spotfire? Table Lens? Any other tool? Please specify.

B.2 Task-list

The experimenter kept a copy of the task list and read aloud the tasks to the users. The first part of the task list contains the tasks assigned in phase 2, during the “think aloud” phase. The second part contains tasks assigned in phase 3, which was timed.

Task List - untimed tasks

I will read each task out loud to you. Try to think of how you would perform a given task, and think might be more than one ways of getting to the solution. Spend time thinking of what you should do to achieve the goal, and then once you know what you can do, perform the task.

Try to do the task by yourself, but in case you are stuck, ask me for help.

We want to find good places to live. Identify 2 cities that have a crime rate lower than average and are values for arts and recreation higher than average.

Identify any two cities that are similar (values within ± 300) to each other on basis of climate, housing and healthcare values. How are the same two cities related considering education, arts and recreation instead?

Find out two cities that have "climate" and "transportation" criteria better than "Jersey City, NJ"

Can you notice any relationship between "climate" and "housing"? Does "economy" affect the housing and climate too? Identify the outliers.

Get details about the city that is most similar to "New York" in terms of crime rate and economics

Consider only the cities that have low cost of housing and low crime, what can you say about the education values for those cities? Do most of these cities have recreation greater or lesser than average?

Task List - timed tasks

This phase is a set of timed tasks. The type of tasks will be similar to the ones you did in the previous phase. However, this time, try to do the tasks as quickly and efficiently as you can. Please attempt to do the task on your own, without interruption. Do not think aloud or make comments during the tasks - that will throw off the timing. If you have comments, make them after the task has been completed.

We want to find out places where you wouldn't want to live.

Identify 2 cities that have very housing value higher than average, higher than average crime rate but lower than average score on education.

Identify any two cities that have low crime rate, low cost of housing and high education and are similar (values within ± 300). How are the same two cities related considering healthcare, transportation and climate instead?

Find out two cities that have lower values for "crime" and "housing" and higher value for "climate" criteria than "Jacksonville, FL"

How are arts and recreation related to each other? Is education related to either or both of them? Identify the outliers.

Get details about the city that is most similar to " Florence, SC" in terms of education and cost of housing

Consider only the cities that have high values of arts and recreation, what can you say about the education values for those cities? Do most of these cities have economics greater or lesser than average?

B.3 Comfort ratings form

1 = normal conditions (comfortable)
 5 = moderate discomfort
 10 = extreme discomfort

After VE familiarization:

arm strain:	1	2	3	4	5	6	7	8	9	10
hand strain:	1	2	3	4	5	6	7	8	9	10
dizziness:	1	2	3	4	5	6	7	8	9	10
nausea:	1	2	3	4	5	6	7	8	9	10

After initial practice:

arm strain:	1	2	3	4	5	6	7	8	9	10
hand strain:	1	2	3	4	5	6	7	8	9	10
dizziness:	1	2	3	4	5	6	7	8	9	10
nausea:	1	2	3	4	5	6	7	8	9	10

After phase 2:

arm strain:	1	2	3	4	5	6	7	8	9	10
hand strain:	1	2	3	4	5	6	7	8	9	10
dizziness:	1	2	3	4	5	6	7	8	9	10
nausea:	1	2	3	4	5	6	7	8	9	10

After phase 3:

arm strain:	1	2	3	4	5	6	7	8	9	10
hand strain:	1	2	3	4	5	6	7	8	9	10
dizziness:	1	2	3	4	5	6	7	8	9	10
nausea:	1	2	3	4	5	6	7	8	9	10

B.4 Post experiment questionnaire

Please rate on a scale of 1 to 7 how you found some of the interaction techniques

Interaction with the menu system used on the right hand

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Using overview attached to left hand to observe trends and get the big picture

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Interaction with detail view (floating in space) to get specific details

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Ability to jump between the two views & interact using the two views

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Able to get different views of the dataset by interacting with the overview (view attached to the left hand)

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Selecting a single point by reaching out for it

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Selecting a number of points by drawing a box around

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Changing attributes

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Ability to choose from a scrolling list

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Moving a point to origin

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Zooming in on a selection of points

a) Ease of learning	low	1	2	3	4	5	6	7	high
b) Ease of use	low	1	2	3	4	5	6	7	high
c) Usefulness in Info Vis	low	1	2	3	4	5	6	7	high

Please answer some other questions about the entire environment

The environment provided the functionality needed to visualize the data.

Disagree 1 2 3 4 5 6 7 Agree

Two-handed interaction helps the visualization

Disagree 1 2 3 4 5 6 7 Agree

Using the overview at the side of the view (the tiny overview shown in the blue box on the bottom left) of the screen, was that helpful?

Disagree 1 2 3 4 5 6 7 Agree

Was adequate feedback provided?

Too little feedback 1 2 3 4 5 6 7
adequate

Was the help provided on the tablet useful?

Too little help 1 2 3 4 5 6 7 adequate

Did you have trouble with the equipment? HMD? Pinch gloves?

None whatsoever 1 2 3 4 5 6 7 Lots of problems

Do you think such a environment helps to get a better idea of the data set?

Not really 1 2 3 4 5 6 7 Yes

Do you feel satisfied with your experience? Is this something you would want to do again?

No 1 2 3 4 5 6 7 Yes

Please feel free to put down any comments

Thanks for your help!!

Appendix C – Forms used in experiment 2

C.1 Pre-experiment Questionnaire

Please help us to categorize our user population by completing the following items.

Gender (circle one): Male Female

Age: _____

Do you wear glasses or contact lenses (circle one)?

No Glasses Contact Lenses

Occupation (if student, indicate graduate or undergraduate):

Major / Area of specialization (if student):

Rate your familiarity with Virtual Environments: (circle one)

•-----•-----•-----•-----•-----•

none very little some VE experience lot of VE exposure experienced in VEs

Have you ever used a virtual reality (VR) system? If so, please describe it (what type of display was used, what kind of application (e.g. architectural walk-through) was running, how did you interact with the system, etc.).

Rate your exposure to 3D games (Quake, doom, descent, etc)

•-----•-----•-----•-----•-----•

none very little some quite a lot trigger happy !

C.2 Subject Comfort Ratings Form

1 = normal conditions (comfortable) 5 = moderate discomfort

10 = extreme discomfort

After VE familiarization:

Arm strain	1	2	3	4	5	6	7	8	9	10	Hand strain	1	2	3	4	5	6	7	8	9	10
Dizziness	1	2	3	4	5	6	7	8	9	10	Nausea	1	2	3	4	5	6	7	8	9	10

After 1st set of trials:

Arm strain	1	2	3	4	5	6	7	8	9	10	Hand strain	1	2	3	4	5	6	7	8	9	10
Dizziness	1	2	3	4	5	6	7	8	9	10	Nausea	1	2	3	4	5	6	7	8	9	10

C.3 Interview Sheet

Did you have trouble with the equipment? HMD? mouse? Wand?
None whatsoever 1 2 3 4 5 6 7 Lots of problems

Did you get a good understanding of the room around you? Various
objects and your position with respect to these objects?
Not really more in VR more on the desktop Yes, in both

Did you ever get the feeling that you didn't know where you were
in the room? Did you get disoriented
No Yes I really don't know

Did you feel lost at any time? Was this feeling more in one
environment than the other?
No, never felt more in VR more on the desktop Yes, in both
that way

Which way of using the probe did you prefer?
Mouse Wand No preference

Do you feel it was easier to understand the effect of
radioactivity more in one environment as against the other?
No, never felt that way yes, more in VR yes, more on the
way desktop

Appendix D - Results of experiment 1

D.1 Timings of tasks

Subject#	Non VE-users					avg	std dev	VE Users					avg	std dev	group average
	1	2	3	4	5			1	2	3	4	5			
task 1	133	32	31	121	31	70	52.6	66	117	120	68	124	99	29.3	84.3
task 2a	105	41	66	67	35	63	27.6	63	119	41	45	92	72	33.1	67.4
task 2b	62	46	42	34	111	59	30.8	76	68	84	62	47	67.4	14.1	63.2
task 2 sum	167	87	108	101	146	122	33.4	139	187	125	107	139	139.4	29.7	130.6
task3	141	96	134	174	140	137	27.8	88	172	225	83	97	133	62.9	135
task 4a	77	52	68	69	38	61	15.6	55	107	60	59	63	68.8	21.5	64.8
task 4b	60	22	61	59	98	60	26.9	60	76	42	42	36	51.2	16.5	55.6
task 4c	59	80	29	39	45	50	19.8	32	55	60	42	40	45.8	11.5	48.1
task 4 sum	196	154	158	167	181	171	17.3	147	238	162	143	139	165.8	41.3	168.5
task 5	95	48	50	213	70	95	68.5	57	73	101	85	90	81.2	16.9	88.2
task 6a	107	37	79	106	51	76	31.7	65	59	110	69	60	72.6	21.3	74.3
task 6b	126	45	72	45	117	81	38.7	38	106	99	35	62	68	33.3	74.5
task 6 sum	233	82	151	151	168	157	53.8	103	165	209	104	122	140.6	45.8	148.8

D.2 Post experiment Questionnaire results

Subject #	Non VE-users					VE Users					
	1	2	3	4	5	1	2	3	4	5	
1	Interaction with the menu system used on the right hand										
	Ease of learning	6	7	7	6	7	6	7	7	6	7
	Ease of use	6	7	6	4	7	5	5	5	6	7
	Usefulness in infovis	5	7	6	3	7	4	6	1	6	7
8	Changing attributes										
	Ease of learning	5	7	7	7	6	6	7	7	6	7
	Ease of use	6	7	7	7	6	7	7	7	7	7
	Usefulness in infovis	6	7	7	7	6	6	7	7	7	7

2	Using overview attached to left hand to observe trends and get the big picture										
	Ease of learning	3	6	4	6	7	5	7	6	7	7
	Ease of use	3	5	4	5	7	6	6	6	7	7
	Usefulness in infovis	3	5	6	5	6	3	7	7	7	7
5	Able to get different views of the dataset by interacting with the overview										
	Ease of learning	6	5	6	6	5	5	7	6	6	7
	Ease of use	6	5	4	6	5	6	7	7	7	7
	Usefulness in infovis	7	5	6	6	6	4	7	7	7	7
B	Two handed interaction helps the visualization										
	disagree-agree	6	7	6	6	3	5	7	5	7	7
3	Interaction with detail view (floating in space) to get specific details										
	Ease of learning	5	7	5	6	6	5	7	4	4	7
	Ease of use	5	6	5	6	4	5	7	5	2	6
	Usefulness in infovis	4	7	6	6	6	5	7	5	2	7
6	Selecting a single point by reaching out for it										
	Ease of learning	4	7	6	2	2	6	7	6	4	7
	Ease of use	5	7	5	2	2	5	4	5	2	6
	Usefulness in infovis	6	7	6	2	6	5	7	2		7
4	Ability to jump between the two views & interact using the two views										
	Ease of learning	3	6	4	5	3	6	7	2	4	7
	Ease of use	3	6	5	5	4	7	5	4	3	7
	Usefulness in infovis	4	6	6	5	5	4	7	6	3	7
7	Selecting a number of points by drawing a box around										
	Ease of learning	2	6	5	5	3	5	5	2	3	7
	Ease of use	3	6	5	4	3	5	5	4	3	7
	Usefulness in infovis	5	7		4	6	5	7	7		7
11	Zooming in on a selection of points										
	Ease of learning	3	6		6	4	4	6	4	5	5
	Ease of use		7		6	4	5	6	6	7	6
	Usefulness in infovis	5	7		6	4	4	6		7	7
9	Ability to choose from a scrolling list										
	Ease of learning	6	7	6	7	6	6	6	6	7	7
	Ease of use	6	7	6	7	6	5	7	6	5	7
	Usefulness in infovis	6	7	7	7	6	5	7	7	7	7
10	Moving a point to origin										
	Ease of learning	4	7	5	7	6	4	5		5	7
	Ease of use	4	7	6	7	6	4	6		3	6
	Usefulness in infovis	5	7	6	7	6	3	6		6	7

	Non VE-users					VE Users				
	1	2	3	4	5	1	2	3	4	5
Subject#	10	7	4	12	13	11	8	5	6	14
A	The environment provided the functionality needed to visualize the data?									
	disagree-agree	6	7	6	6	6	7	6	6	7
F	Do you think such a environment helps to get a better idea of the data set?									
	disagree-agree	5	6	6	5	3	7	7	5	6
H	Do you feel satisfied with your experience? Is this something you would want to do again?									
	no - yes	6	7	7	4	4	6	7	4	5
C	Using the overview at the side of the view of the screen, was that helpful?									
	disagree-agree	3	6	2	4	3	2	3	1	1
D	Was adequate feedback provided?									
	too little - adequate	4	7	7	5	7	5	7	2	5
E	Was the help provided on the tablet useful?									
	too little - adequate	4	6		2	5	4	4		2
F	Did you have trouble with the equipment? HMD? Pinch gloves?									
	none - lots	2	1	2	7	6	3	5	4	2

D.3 Comfort ratings

	Non VE-users					VE Users						
	1	2	3	4	5	1	2	3	4	5	Avg	std dev
Subject#	10	7	4	12	13	11	8	5	6	14		
VE familiarization												
arm strain	4	1	5	1	1	1	1	2	1	1	1.8	1.48
hand strain	3	1	1	1	1	1	1	2	1	2	1.4	0.70
dizziness	2	1	1	1	3	1	1	5	1	1	1.7	1.34
nausea	1	1	1	1	1	1	1	3	1	1	1.2	0.63
Initial practice												
arm strain	3	1	5	1	3	2	1	2	2	1	2.1	1.29
hand strain	2	1	1	1	1	1	2	2	2	1	1.4	0.52
dizziness	1	1	1	5	4	1	2	5	1	1	2.2	1.75
nausea	1	1	1	1	1	1	1	3	1	1	1.2	0.63

Session 2													
arm strain	2	1	3	1	2	1	1	1	2	1	1.5	0.71	
hand strain	2	1	1	1	1	2	1	2	1	2	1.4	0.52	
dizziness	2	1	1	2	4	1	1	3	4	6	2.5	1.72	
nausea	1	1	1	1	1	1	1	2	6	3	1.8	1.62	
Session 3													
arm strain	3	1	1	3	2	1	1	2	1	1	1.6	0.84	
hand strain	2	1	1	2	1	1	1	2	1	2	1.4	0.52	
dizziness	2	1	1	1	6	1	1	5	6	5	2.9	2.28	
nausea	1	1	1	1	1	1	1	2	6	5	2	1.89	

Appendix E – Results of experiment 2

E.1 Timings

	Participant Subject #	VE First									Desktop First								Avg	
		1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8		
Gender VE exp. Games exp.		2	4	7	9	11	12	15	17		3	5	6	8	10	13	14	16	83	
		f	m	m	f	f	f	m	m		m	m	f	f	m	m	m	m		
		1	2	5	5	2	0	1	3		3	3	2	3	3	3	5	2		
VE Trials		1	2	4	1	1	1	1	1		4	4	1	2	5	3	5	2	83	
		1	2	3	4	5	6	7	8		62	120	115	145	67	152	28	52		
		2	90	82	90	79	94	182	71	114		52	59	93	131	71	71	40		80
		3	90	34	86	61	130	158	74	151		71	76	191	71	64	61	35		0
		4	135	72	78	51	75	223	73	179		86	100	131	112	51	52	30		53
	Average	97	65	79	56	93	166	85	145	98	68	89	133	115	63	84	33	79		
	Std Dev	26	21	12	20	27	51	25	28		14	27	42	32	9	46	5	37		
Desktop Trials		1	2	3	4	5	6	7	8		69	285	195	135	80	159	46	4	103	
		2	120	84	64	97	175	115	113	165		89	67	166	69	59	89	52		7
		3	131	183	58	90	79	95	79	114		89	146	150	82	70	52	43		8
		4	180	157	51	59	78	105	65	47		78	60	240	147	18	60	47		36
		Avg	145	153	59	82	126	91	119	117	111	81	140	188	108	57	90	47		6
	Std Dev	26	48	6	17	55	29	70	51		10	105	40	39	27	49	4	63		

E.2 Errors

	Participant Subject #	VE First								Desktop First							
		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Gender VE exp. Games exp.		f	m	m	f	f	f	m	m	m	m	f	f	m	m	m	m
		1	2	5	5	2	0	1	3	3	3	2	3	3	3	5	2
		1	2	4	1	1	1	1	1	4	4	1	2	5	3	5	2
VE Trials		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
		3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
		4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Count	2	0	0	0	1	2	0	0	0	0	1	1	0	0	0

Desktop Trials	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	2	1	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0
	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	0
		2	1	0	0	1	0	0	0	0	0	1	3	0	1	1	0

Appendix F – Statistical Analysis of Experiment 2

F.1 The GLM Procedure for evaluation of timings

The SAS System 21:11 Thursday, April 26, 2001 11
 The GLM Procedure
 Class Level Information

Class	Levels	Values
Cdt	2	1 2
User	16	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Number of observations 128

Dependent Variable: y

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	109653.7187	3537.2167	1.64	0.0364
Error	96	207528.0000	2161.7500		
Corrected Total	127	317181.7188			

R-Square	Coeff Var	Root MSE	y Mean
0.345713	46.98651	46.49462	98.95313

Source	DF	Type I SS	Mean Square	F-Value	Pr > F
cdt	1	9146.2813	9146.2813	4.23	0.0424
user(cdt)	30	100507.4375	3350.2479	1.55	0.0571

Source	DF	Type III SS	Mean Square	F-Value	Pr > F
cdt	1	9146.2813	9146.2813	4.23	0.0424
user(cdt)	30	100507.4375	3350.2479	1.55	0.0571

Tests of Hypotheses Using the Type III MS for user(cdt) as an Error Term

Source	DF	Type III SS	Mean Square	F-Value	Pr > F
cdt	1	9146.28125	9146.28125	2.73	0.1089

F.2 The GENMOD Procedure for analysis of error count

The SAS System

1

The GENMOD Procedure

Model Information

Data Set	WORK.ONE
Distribution	Normal
Link Function	Log
Dependent Variable	y
Observations Used	128

<i>Criteria For Assessing Goodness Of Fit</i>			
Criterion	DF	Value	Value/DF
Deviance	124	16.4554	0.1327
Scaled Deviance	124	128	1.0323
Pearson Chi-Square	124	16.4554	0.1327
Scaled Pearson X2	124	128	1.0323
Log Likelihood		-50.3361	
Algorithm converged.			

<i>Analysis Of Parameter Estimates</i>							
Parameter	DF	Estimate	Standard Error	Wald Limits	95% Confidence	Chi-Square	Pr > ChiSq
Intercept	1	-2.3319	1.1924	-4.6689	0.0052	3.82	0.0505
cdt	1	0.2257	0.4874	-0.7295	1.1809	0.21	0.6432
user	1	-0.0605	0.0752	-0.2079	0.0869	0.65	0.4215
trial	1	0.1698	0.1908	-0.2042	0.5439	0.79	0.3735
Scale	1	0.3585	0.0224	0.3172	0.4053		

NOTE: The scale parameter was estimated by maximum likelihood.

LR Statistics For Type 3 Analysis			
Source	DF	Chi- Square	Pr > ChiSq
cdt	1	0.22	0.6379
user	1	0.77	0.3792
trial	1	0.83	0.3621

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Vita

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