Doug A. Bowman
bowman@cc.gatech.edu

Larry F. Hodges
hodges@cc.gatech.edu

Don Allison
don@cc.gatech.edu
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280

Jean Wineman
jean.wineman@arch.gatech.edu
College of Architecture
Graphics, Visualization, and Usability Center
Georgia Institute of Technology
Atlanta, Georgia

The Educational Value of an Information-Rich Virtual Environment

Abstract

Information-rich virtual environments consist not only of three-dimensional graphics and other spatial data but also information of an abstract or symbolic nature that is related to the space. An environment of this type can stimulate learning and comprehension, because it provides a tight coupling between symbolic and experiential information. In our virtual zoo exhibit, students can explore an accurate model of the gorilla habitat at Zoo Atlanta and access information related to the design of the exhibit. This paper discusses the design of the application and the interaction techniques used to obtain information. We also present the results of a formal evaluation. Although no statistically significant differences were found, results indicate that students who used the virtual environment had higher test scores than those who only attended a lecture on the material. Trends suggest that the virtual experience allowed students to learn information directly and also equipped them to better learn and understand material from a traditional lecture.

1 Introduction

The goal of virtual environment (VE) research is not to produce more realistic environments, faster 3-D graphics, better sensory cues, or low latency. Rather, all of these are only the means by which we hope to achieve the actual end: useful applications that will benefit people. Although most are still in the research lab, a few categories of VE systems have shown great promise, including architectural walkthrough (Brooks, Airey, Alspaugh, & Bell, 1992), exposure therapy for phobias (Hodges, Rothbaum, Kooper, Opdyke, Meyer, North, de Graff, & Williford 1995), and training for hazardous duty (Tate, Sibert, & King, 1997). All of these share the characteristic that their success depends only on producing a satisfactory and believable experience to the user; i.e., they must cause the users to suspend their disbelief and to feel on some level that they are actually in the displayed environment (immersion).

It has been suggested that education should be another key application area for VEs (Durlach & Mavor, 1995), and this follows from the argument that the experience should be the main ingredient of a successful VE. After all, experience is the best teacher. However, the amount of published work in this area is small, and the number of systems that have been shown to be practical is even smaller. Why?

It seems that experience can take a student only part of the way to learning and understanding a subject. In most cases, it is necessary to have background

Presence, Vol. 8, No. 3, June 1999, 317–331

knowledge, peripheral information, reflection, *and* experience before the subject can be comprehended by the student. Consider that high-school students have experienced a phenomenon such as the refraction of light many times, but they do not come to a complete understanding of it until they study optics in their physics classes.

Thus, experience is only one part of a practical education. In fact, it is dangerous to rely solely on experiences for learning, since incorrect mental models can often arise logically from experiential data (for example, one could draw the incorrect conclusion that acceleration due to gravity is based on an object's mass by observing that a brick falls faster than a feather). Certainly, some concepts cannot be experienced directly in the world, such as the interactions between subatomic particles. In cases such as this, a virtual environment can provide an important first step in understanding, but other knowledge and teaching will also be necessary to produce complete comprehension.

This paper presents an educational virtual environment that provides both experiential and abstract information in a tightly coupled manner. In this way, students can avoid the pitfall of relying only on experience as a learning tool and also have the opportunity to relate information that would normally be received in a lecture setting to an actual experience and a three-dimensional space. We call this an *information-rich* virtual environment (Bowman, Hodges, & Bolter, 1998).

Our system builds on the work of the virtual reality gorilla exhibit (Allison, Wills, Hodges, & Wineman, 1997), and is designed to teach college students about the design principles used in constructing an animal habitat within a zoo setting. Users can move about the habitat to see it from any point of view, and can also obtain information (text, audio, or image) relating to the design of various aspects of the exhibit. Before we discuss the specifics of the application, we will review some related work in educational and information-rich VEs. After describing the system, we will present an evaluation in which we tested the educational value of our system in the context of a college course on environmental design. We will conclude with a discussion of the results and further work that we hope to do in this area.

2 Related Work

2.1 Information-Rich Virtual Environments

Many systems have been developed that use a three-dimensional space to present some form of information to the user. These include both immersive virtual reality systems and desktop 3-D applications. Let us consider two categories of such systems: scientific simulations and database visualizations.

Scientific simulations present views of scientific data within a 3-D environment, often with animated objects. Generally, they consist of abstract objects that are too small for the naked eye (such as atoms (Bergman, Richardson, Richardson, & Brooks, 1993)), too large to be comprehended (such as the solar system (Song & Norman, 1993)), or invisible (such as electromagnetic fields (Dede, Salzman, & Loftin, 1996) or fluid flow lines (Bryson & Levit, 1992)). Users can examine these simulations from various positions, detect patterns that would not be obvious without the visualization, and make changes to conditions and immediately visualize the results.

Database visualizations take a complex and abstract dataset and organize it into an understandable visual representation that can be navigated and accessed by the user (e.g., Benford, Snowdon, & Mariani, 1995; Fairchild, Poltrock, & Furnas, 1988; Fairchild, 1993; Risch, May, Thomas, & Dowson, 1996; Robertson, Card, & Mackinlay, 1993). Here abstract properties of the data are mapped into perceptual qualities, such as size, shape, color, or motion, and relationships between pieces of data are represented spatially. The resulting 3-D visualization can reveal patterns in the data due to patterns (such as spatial groupings) that are not obvious from the original dataset.

Both of these types of information spaces present abstract or nonviewable information using a perceptual (geometric) form. Other forms of information, such as text or speech (symbolic information) are not usually present except as labels for the geometric objects. On the other hand, information-rich virtual environments embed symbolic information within a realistic 3-D environment. For example, a virtual college campus may contain text describing various streets or buildings or spoken audio giving the characteristics of the athletic facilities. In this way, symbolic and perceptual information are integrated in a single environment (Bolter, Hodges, Meyer, & Nichols, 1995).

Our previous work in the area of information-rich VEs was conducted in the context of an application called the Virtual Venue (Bowman, Hodges, & Bolter, 1998). In this system, users could move about an accurate model of the Georgia Tech Aquatic Center, and obtain various types of information regarding the design and use of the venue and the sports of swimming and diving. A usability study revealed that the most effective types of information were those that were "tightly coupled" to the environment, i.e., the information content was pertinent to or otherwise associated with the object or location in 3-D space.

Experience with the Virtual Venue indicates that information-rich VEs can be an effective means of information retrieval, but our usability study did not allow us to compare it with other information-gathering media, such as multimedia presentations, the Web, or printed text. Thus, in our current study, we have created a comparison between traditional lectures and classroom teaching augmented with the use of a virtual environment.

2.2 Educational Virtual Environments

Wickens (1992) gives an overview of some of the salient features of virtual reality and their relation to education. He argues that the closed-loop interaction style of VEs should increase learning and retention, because it requires effort on the part of the user to continuously choose his position, view orientation, and action, rather than being passively guided by the system. However, some of the other characteristics of VEs, such as three-dimensional and ego-referenced viewing, and "natural" interaction, may actually reduce a student's retention because he has not been required to put forth as much effort. Thus, he claims that the goals of user-interface design (e.g., reduce mental workload for the user) and educational software design actually conflict in some ways.

We would argue that a distinction needs to be made between cognitive load from task-related activities and system-related activities. That is, Wickens is correct that, in educational environments, learning activities (task related) should require effort and choice on the part of the user; however, system-related activities, such as selecting an object, changing display mode, or finding a menu item should require as little cognitive processing as possible. We do not want users to be distracted from learning because they cannot figure out how to use the interface.

Wickens also highlights the need for educational systems to teach the relationships between pieces of information, rather than just isolated facts. He observes that "the educational benefit of a VR experience should be enhanced to the extent that the learner is exposed to material from *both* a VR and a more abstract perspective, and learner attention is directed to the linkages or relatedness between these two perspectives" (Wickens, 1992). This is precisely the goal of an information-rich VE: users obtain both spatial and abstract information within the same context, and the relationships between the two are made evident by the location and type of embedded information. Learning information in various forms and learning the relationships between pieces of information should give the student more opportunities to later retrieve the information.

Several reported VE systems are intended for educational purposes, and it will be instructive to review some of them here. As we have already mentioned, some scientific simulations and data visualizations could be considered educational, since they "teach" the user information that might not have come to light without the 3-D visualization. However, in the case of applications such as the virtual wind tunnel (Bryson & Levit, 1992), the users are already experienced in the field of computational fluid dynamics, and thus can understand the visualization as presented. Thus, such systems are not teaching concepts, but instead are demonstrating or applying concepts that may then reveal further specific information.

Two scientific simulation applications are intended for conceptual education, however. The ScienceSpace system (Dede et al., 1996) and a VR physics simulator from

Rice University (Brelsford, 1993) are both designed to teach important physics concepts using an immersive virtual environment. Both of these systems use a constructivist educational theory, meaning that students learn through personal interaction with the material (in this case manipulating physical elements and observing their behavior).

ScienceSpace has three virtual worlds that teach the concepts of Newtonian mechanics, electrostatics, and molecular structure and dynamics. These worlds are designed to promote learning through experience and experimentation. Thus, students can "become" a point mass to learn about collisions or move a charge through an electric field to see the magnitude and direction of the force on that charge. This allows students to experience phenomena that are not accessible in our physical world, and hopefully gain the ability to predict the results of a given situation. However, the authors acknowledge that incorrect mental models can be created based on experience alone, which could mislead the student. Thus, students are carefully guided through the learning process, with appropriate background information inserted when needed. In fact, the authors say that they are currently developing an automated "coaching" system that will embed feedback into the virtual environment, making it into an information-rich VE. Recently, comparative evaluations of ScienceSpace have indicated that such an environment may increase both learning and retention of information (Dede, Salzman, Loftin, & Ash, 1997).

The Rice physics system is not described in great detail, but is said to be a virtual representation of a physics laboratory, complete with pendulums and masses, and controls to change the force of gravity, location, air drag, friction, and so on. The author describes a study in which both junior-high and college students were divided into two groups: one used the VR system for one hour while the other attended a lecture over the same material. The groups were tested four weeks later, and the results showed that the VR group had increased their physics knowledge by a significantly greater amount. This clearly shows the promise of VR as an educational medium. However, it is difficult to tell from the article how students were given the necessary background information they needed in order to understand the results of their experiments in the virtual laboratory. The authors do say that students worked on specific written problems during their sessions, which may have themselves been sources of abstract information or formulas, and which definitely guided the experimentation of the users.

The predecessor of our current design education application is the virtual reality gorilla exhibit (Allison et al., 1997). The VR gorilla exhibit is also an educational application, designed to teach middle-school students about gorilla behaviors, vocalizations, and social interactions. Students begin in the visitors center, acclimating themselves to the virtual environment and the techniques for movement. By moving through the viewing window, they take on the persona of an adolescent gorilla, and the virtual gorillas in the exhibit react as they would to a young gorilla. The virtual gorillas have accurate movements, sounds, and behaviors, so that, if the user makes a social faux pas, such as entering the personal space of the male silverback, he will see a realistic reaction (escalating annoyance leading to a "bluff charge" and chest beat).

The VR gorilla exhibit originally relied solely on experience to teach the students: it was hoped that they would draw their own inferences from using the system, since the gorillas' interaction was not very complex (Wineman, Hodges, Allison, & Wills, 1997). Some students did this, but most needed assistance to understand the behavior of the virtual animals. This meant that a gorilla expert needed to stand next to the user, offering information and advice to aid the learning process. Eventually, we decided to automate most of this expert information by providing spoken information through headphones at appropriate times, locations, or events (Allison et al., 1997b). For example, when the user stares for too long at an older gorilla, an audio segment informs the user that the gorilla is becoming annoyed because of the staring, and tells the user what she should do to placate the other animal (look away and move away). We also implemented "mood indicators," icons that indicate the current state of each of the virtual gorillas (content, annoyed, or angry).

These enhancements effectively make the VR gorilla exhibit an information-rich VE. Even with the simplicity of the information to be presented, experience alone did not allow total comprehension. Both experience and abstract information were needed to give students a complete understanding.

3 Virtual Zoo Exhibit for Design Education

Our current application of virtual environments for design education uses the habitat model from the VR gorilla exhibit, which is an accurate model of the largest outdoor gorilla habitat at Zoo Atlanta (Figure 1). Elements including the visitors center, moats, terrain, trees, rocks, and logs are all modeled and positioned as they are in the physical exhibit. However, our focus has changed from teaching middle-school students about gorilla behavior to teaching college students about habitat design. The learning goal of the students who use this system is an understanding of the philosophy of environmental design and of the specific design decisions that were made for the Zoo Atlanta gorilla exhibit. Therefore, we have embedded new symbolic information content within the virtual exhibit and have included new interaction techniques with which to access this information.

Like its predecessor, the design education application is based on the Simple Virtual Environment (SVE) library (Kessler, Kooper, & Hodges, 1998), a software support library that takes care of the details of tracking, rendering, event-handling, and the like. The system runs on a Silicon Graphics Indigo2 Max Impact, and uses a Virtual Research VR4 head-mounted display (HMD) for visual output. Tracking is performed using a Polhemus Fastrak with three enabled receivers, including a special stylus with a button. (See Figure 3a.) One tracker is used for head position and orientation, while the other two allow us to implement a "pen and tablet" interaction metaphor (which is described below).

This application is quite different from the other educational VEs that were mentioned earlier. First, our system supports design education, while most previous efforts focused on math or science education. Design is a much less concrete subject, which may make it more difficult to teach. However, students are not required to understand complex formulas, and aesthetics play a major role. These characteristics make design education a natural fit for a VE. Second, our system is not based on constructivist learning, as most previous educational VEs have been. Rather, we chose to present design philosophies in an abstract form within a model of a space that follows those philosophies. For design education, students must be able to see examples of design concepts at work before they can begin to construct their own designs. Our system does incorporate some constructive elements that allow students to modify the habitat's design (Bowman, Wineman, Hodges, & Allison, 1998), but these tools were not used until students had obtained information on design concepts. Finally, as we have stated, our system explicitly integrates both symbolic and perceptual information in a single environment, so that learning and comprehension are enhanced.

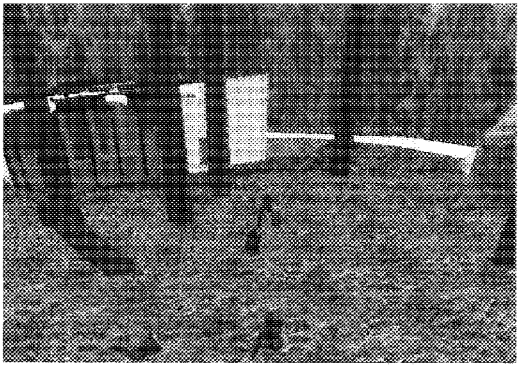

Figure 1. *The Virtual Gorilla Exhibit*

3.1 Embedded Information

The design education application makes use of several embedded media types to accomplish its goal of presenting relevant information about habitat design within the context of the habitat itself. The most ubiquitous form is spoken audio. The virtual habitat contains nine-

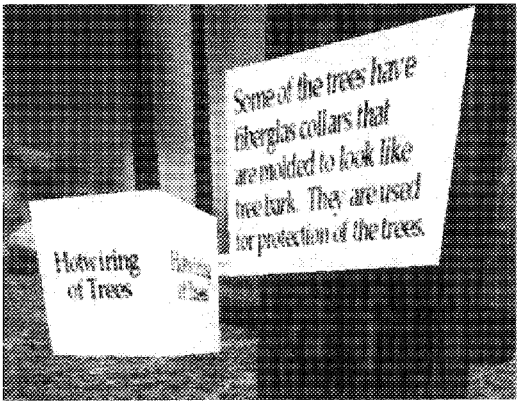

Figure 2. *Audio (left) and text annotations in the virtual habitat.*

teen audio clips describing many aspects of the design. They range from general concepts regarding the philosophy of environmental design to quite specific pieces of information on features of the gorilla habitat itself. Some of the clips are taken directly from a recorded interview with one of the gorilla researchers from Zoo Atlanta. In general, we tried to use audio for most of the embedded information since it allows the user to view the environment at the same time as he is receiving aural information. For example, the student can look at the structure of the moat while listening to an annotation describing its design and construction.

Some audio annotations are played automatically based on the current state of the system or the user's position within the environment. For example, some introductory material is played when the system is initialized, and a description of the design of the outdoor viewing areas is given when the user goes there. Most annotations, however, are represented by cubes in the environment (Figure 2) and are triggered explicitly by the user, as described in the section on interaction techniques. The user therefore explores and learns at her own pace and based on her own interests, rather than under the control of the system. Such annotations are similar to the "voiceholders" used in the Placeholder system (Laurel, Strickland, & Tow, 1994). All of the annotations were developed using a VE audio annotation toolkit (Bowman & Hodges, 1997) developed for the Virtual Venue system.

There are also five text annotations in the virtual exhibit, in the form of signs that are located on surfaces within the environment, such as on the walls of the visitors center or on a tree (Figure 2). Text was chosen over audio for information that might require scanning back and forth and rereading. Audio is obviously less suitable for these purposes. We also inserted text annotations in areas that were already cluttered with audio clips.

Finally, we have embedded two images in the virtual habitat to enhance understanding of text and audio annotations and to convey spatial relationships that would be difficult to describe in words. One of the images is a map of the entire gorilla exhibit at Zoo Atlanta, showing the habitat in plan view and its location relative to the other three gorilla habitats, and illustrating the idea of a "zoogeographic" and "bioclimatic" zone, in which animals and plants from similar geographic and climatic regions are grouped together. Although not all individuals can acquire knowledge easily from maps, this map is not intended to teach a detailed spatial layout; rather, its purpose is to show that the main habitat is surrounded by other habitats containing animals and plants from similar areas of the world. The other image is a photograph of a gorilla playing near the window of the visitors center, which illustrates a point about usage of various areas of the habitat. The picture and an audio clip describing habitat usage are presented simultaneously to the user.

The embedded information was gleaned from a variety of sources. Interviews were conducted with both the principal architect in charge of the design of the gorilla habitat and one of the gorilla researchers at Zoo Atlanta. We also obtained some general information on the philosophy of the designers in several of their publications (Coe, 1985; Coe & Maple, 1987). Finally, we used maps and other information about the zoo that appears on the WWW homepage for Zoo Atlanta (www.zooatlanta.org).

Unlike the VR gorilla exhibit, the virtual gorillas in the design education system do not react to users. Interaction with the virtual gorillas can be very compelling and might distract users from the goal of teaching students about habitat design. Moreover, the behavior of the virtual gorillas is not yet complex enough to inform students' design, as it does not include key behaviors such as feeding or seeking shaded areas. However, we have included stationary gorillas in the environment, and they are used to help underscore some design concepts. The gorillas are positioned on a hillside based on gender and age, which is similar to the observed use of hills by gorillas in the wild. This fact informed the design of the exhibit's terrain and is explained in an audio annotation. Also, the virtual gorillas help to give the student a sense of the scale of the design, which is quite important from an architectural point of view.

3.2 Interaction Techniques

An information-rich virtual environment cannot be effective unless the user can easily and efficiently access the information. For this reason, usable interaction techniques are a necessity and cannot be overlooked. Based on our previous experimentation and experience, we have chosen techniques for user navigation and object selection that exhibit simplicity, efficiency, and unobtrusiveness.

Usable navigation techniques should allow the user to move around the habitat freely and efficiently, while ensuring that the user does not become lost or disoriented in the 3-D space. This is a difficult combination to achieve, since more freedom generally results in higher disorientation, and reducing disorientation depends on constraints, which diminish freedom of movement. Our previous studies on the subject of VE travel techniques (Bowman, Koller, & Hodges, 1997) aided us in combining two techniques that allow complete freedom of movement while also providing aids to reduce disorientation.

The first technique uses the stylus as a pointing device. Users point in the direction in which they wish to move, and hold down the stylus button to travel in that direction with a constant velocity. Users can see a representation of the stylus in the virtual world, so they can visualize the direction they are pointing. Our previous experiments have shown that this technique is accurate and efficient for most user-positioning tasks, whether the user is traveling directly to an object or simply moving to a location to obtain a specific view of the world. The pointing technique decouples the user's head orientation from the direction of travel, allowing him to move in any direction regardless of the direction of his gaze. One important feature of this technique from a design perspective is the ability to fly upwards to get a bird's-eye view of the entire habitat. Darken & Sibert (1993) reported that users could use the flying capability to combine "map reading" (using the real world as a map), navigating, and movement into a single integrated task, and thus increasing their spatial awareness.

Some disorientation is prevented by keeping the user within the habitat using some simple collision-detection routines. Users are not allowed to go below the ground or beyond the walls of the surrounding moat. However, flying in 3-D space is still difficult for many people, and they may not be able to maintain spatial awareness of their surroundings, causing disorientation.

The second technique addresses some of these concerns. It is based on the "pen and tablet" metaphor (Angus & Sowizral, 1995) which we used in the Virtual Venue. In the nondominant hand, the user holds a physical tablet (Figure 3a), and a visual representation of the tablet can be seen in the virtual environment. A map of the habitat appears on the tablet, and a red dot represents the user's current position (Figure 3b). The user can move by placing the stylus over the red dot, holding down the button, and dragging it to a new location on the map. When the button is released, the user is flown smoothly to the new position in the environment.

This technique has several advantages. First, the map displaying the user's position effectively combats disorientation. If the user feels lost, she can look at the map and find her position relative to some known landmarks. This is true whether the user has been using the pointing technique or the dragging technique. Second, by dragging to a specific location on the map, the user can move quickly to the area of interest, without having to navigate through the actual 3-D environment. Third, since the user does not actually change position until she releases the stylus button, she can watch as she travels smoothly from her current location to the new one, and spatial awareness may be maintained. (Passive, system-controlled movement may also cause disorientation, but

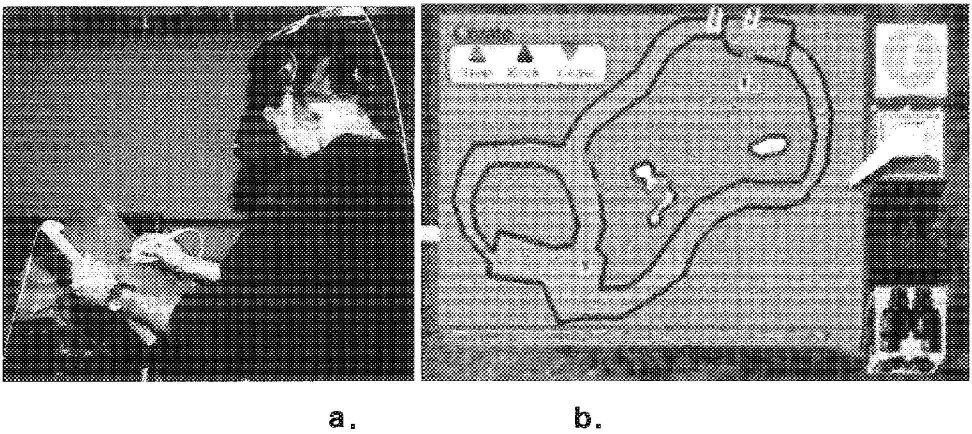

Figure 3. *a) Physical devices used in the "pen and tablet" interaction metaphor; b) User's view of the virtual tablet and stylus.*

the availability of the active-pointing travel technique mitigates this effect.) Also, the pen-and-tablet metaphor itself has several advantages for many types of interaction, due to its unobtrusiveness (the tablet may be put aside if not needed), its inherent constraint (the physical surface of the tablet guides the stylus), and its use of two-handed interaction, with the dominant hand working relative to the nondominant hand (Hinckley, Pausch, Proffitt, Patten, & Kassell, 1997).

We considered a "view-up" map which rotates so that the map is constantly aligned with the user's point of view. However, Wickens (1992) and others have argued that such a display, while possibly enhancing navigation performance, may reduce retention of the layout of the 3-D space. We have instead given users a fixed frame of reference within the egocentric frame of reference, which forces them to expend some effort in forming mental links between the two types of views, and should cause increased retention of the spatial data.

The user can combine the two navigation techniques in any way. In our experience, most users utilize the pointing technique for exploration and obtaining interesting views of the habitat, and the dragging technique to quickly move to a new area when the information-gathering task demands it. The map and the constraints on movement help the users maintain awareness of their spatial location.

Our application also required a technique for object selection, because we wished to allow users to control the playback of audio annotations. Audio clips were represented by white cubes within the environment itself (Figure 2), on which were printed a title phrase so that users could know the theme of the annotation without playing it. (This also prevented users from mistakenly playing the same annotation over again.) The annotations were also represented by icons on the map, so that users would be able to see the location of audio information and move to these locations more quickly.

The user selects the cube to begin playback, and she can also stop it during playback by selecting the cube again. There are several requirements for the selection technique. First, it must be cognitively simple to use, because we want students to focus on the content of the annotations and not on the interaction. Second, it should be useful at a distance, because users need to be able to look around the environment while the annotation is playing. If they are forced to move in close proximity to the cube, it might block their view. Finally, the selection technique should integrate nicely with the navigation techniques we have chosen.

In a previous study on selection and manipulation techniques for immersive VEs (Bowman & Hodges, 1997), we found that the ray-casting technique, in which the user points a virtual light ray at an object to

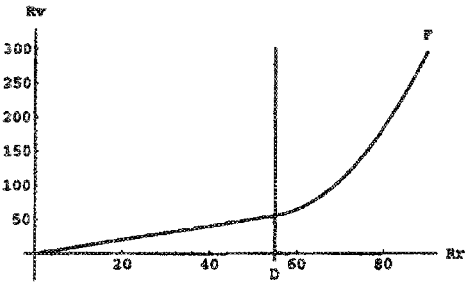

Figure 4. *Nonlinear function for virtual arm length using the go-go technique (reproduced from Poupyrev et al., 1996). Rr = real hand-body distance (cm), Rv = virtual hand-body distance (cm).*

select it, was nearly optimal for object selection (although it was not as useful for manipulation). Unfortunately, this technique requires a button to activate the light ray, and our stylus button was already being used by the pointing technique for navigation. We could leave the light ray active at all times, but this might obscure views of the environment. Instead, we chose to use the "go-go" technique (Poupyrev, Billinghurst, Weghorst, & Ichikawa, 1996) for object selection. This technique allows the user to stretch his virtual arm well beyond the length of his physical arm, using the mapping function shown in Figure 4. When the physical hand is beyond a certain distance (D) from the user's body, the virtual arm begins to grow at a nonlinear rate. Our study showed this technique to be nearly as efficient for object selection as ray-casting, although it may not be as accurate for small objects. Since our annotation cubes were fairly large, the go-go technique would allow easy object selection from a distance with no change to our navigation techniques.

4 Evaluation and Testing

In order to test the efficacy of our VE system for design education, we designed and implemented an evaluation within the context of a class on "The Psychology of Environmental Design," taught jointly by the College of Architecture and the Department of Psychology. The class already contained a major section on the design of zoo exhibits, so our system fit neatly into the content of the class.

The evaluation was designed to test two hypotheses:

1. Students who augment the normal class presentations by using the virtual zoo exhibit will have greater understanding and increased retention of the material, and thus will perform better in an evaluation.
2. Students who use the virtual zoo exhibit will be better equipped to learn when the same material is presented in class and will be able to form more mental associations, and thus will perform better in an evaluation.

Note that in neither of these cases do we surmise that the virtual zoo exhibit should replace traditional classroom teaching; rather, it is best used as a supplement to the normal procedure of the class. It would be extremely difficult to create an information-rich VE that would gracefully contain the complexity of the material that could be presented in an hour-long lecture. Therefore, the VE is better suited to introduce material, create associations between abstract and spatial information, and to equip students for further learning.

4.1 Method

The class of 24 students was divided into three groups: two groups of nine students and one group of six. Equal groups of eight students each were not possible, because the instructor wished to divide the class based on project teams, each of which had three members. The groups are summarized in Table 1. Students were randomly assigned to project teams, and project teams were randomly assigned to groups.

The control group (nine students) had no change to the normal progress of the course. That is, they simply attended lectures, one of which covered material on exhibit design in general and the design of the gorilla habitat in particular.

The information group (nine students) attended class lectures and also used the VE system to explore the virtual habitat and to gather embedded information. This

Table 1. *Summary of Experimental Groups*

	Information	Habitat	Control
Initial # students	9	6	9
Final # students	8	3	5
VE usage	complete	habitat only	none

Table 2. *Evaluation Test Summary*

Test subsets	# questions
V: VE-only	5
L: Lecture-only	12
B: Both	9

was done in two phases: first, students explored the habitat with information disabled, in order to understand the layout of the exhibit; second, students gathered information within the VE using the techniques described above. Students were not given a time limit, but it was suggested that they spend five to ten minutes in phase 1 and ten to fifteen minutes in phase 2.

The habitat group (six students) attended class lectures and also used the VE system to navigate about the virtual gorilla habitat. They were able to explore the visitors building, the hillside, moats, and rocks, and they could also fly into the air to get a bird's-eye view of the environment (the same opportunities as the information group in phase 1). However, this group could not access any of the embedded information. The students were given no time limit, but it was suggested that they spend less than twenty minutes. This group was used as a check to ensure that any performance differences were due to the coupling between the information and the virtual environment, and not just because the novelty of the VE experience motivated higher learning during lectures.

Before their VE sessions, each of the students in the information and habitat groups received both written and verbal instructions on the use of the system as appropriate. They also signed an informed consent form and completed a background questionnaire that inquired about their age, gender, handedness, college major, computer usage and experience, and VE experience. Students completed their use of the VE before the class lecture took place. They were told that they were simply trying a new computer system that might be used in later classes, and were naive regarding the purposes of the experiment.

In the class period after the lecture on this material (five days later), an unannounced test was given to all students in the class. The test covered material relating to the philosophy of zoo exhibit design and specific information about the design of the gorilla habitat at Zoo Atlanta. At the conclusion of the test, students were told about the nature and purposes of our evaluation.

The test consisted of 26 questions, 24 fill-in-the-blank and 2 multiple-choice. Also, there were three subsets of questions relative to the information presented: five of the questions could be answered only from material presented in the VE, twelve of the questions could be answered only from material presented in the lecture, and nine of the questions concerned material that was given in both the VE and the lecture (Table 2). Analysis of scores on these three subsets could help to show which of our two hypotheses, if either, was correct. If the information group scored higher on the questions relating only to the VE or to both the VE and lecture, the first hypothesis would be supported (students learned and understood more material because they encountered that information in the VE). If the information group scored higher on the questions that came only from the lecture, then our second hypothesis would be supported (students were better equipped to learn from the lecture because of the VE experience).

Unfortunately, the size of the three groups was reduced due to imperfect class attendance. Some students did not attend the lecture class, and others were absent on the day of the test. This left the control group with five students, the habitat group with three students, and the information group with eight students.

4.2 Observations of System Usage

Use of the VE application by students in the information and habitat groups provided us with some interesting information on how students are likely to use such educational VEs, how well we addressed usability issues, and how well abstract information was embedded within the 3-D environment.

Students in the information group had little trouble finding the embedded information. The annotations themselves were easily visible within the environment, and some students also used the map extensively to locate information they had not yet accessed. Once the annotations were found, it was not clear how well students integrated this abstract information with their environment. We noted two or three students looking at the area described in an audio annotation, or even navigating to get different views of that area, while the annotation was playing. For the most part, however, students seemed to be listening to the audio information without attempting to relate it to the environment, indicating that perhaps the relationship between the audio and the environment needed to be more clear.

Navigation techniques produced few usability problems. As we surmised, we observed students using the pointing technique mainly for exploration of the habitat (e.g., phase 1 for the information group), and the pen-and-tablet technique for goal-directed travel (e.g., to move to an area with embedded information). Several students did have difficulty with 3-D flying using the pointing technique, but found they could move effectively by pointing slightly downward at all times, which had the effect of keeping them at ground level.

One interesting artifact of the pointing technique which we noted here, as well as in other contexts, is that, because it allows users to move in any direction without regard to head orientation, users tend to face almost exclusively in one direction. This seems natural to most users who have experience only with nonimmersive displays. Thus, in this system, users would begin in the visitors center, facing toward the window looking out into the habitat, and would remain facing this way for most of the session. This severely limited the diversity of viewpoints students could obtain of the habitat. Students generally turned around only when reaching the far end of the habitat or when prompted by the experimenter. When they realized that turning allowed them to obtain different views and a better understanding of the space, students began to use this feature more often.

Selection of audio annotations using the go-go technique was mostly successful, but some information group students had difficulty with the technique. Conceptually, students easily understood the "magic arm" idea, but some attempted to activate the audio annotations from great distances in the environment. Since the go-go technique produces a large virtual arm movement from a small physical arm movement at large distances, it was difficult for these students to position the virtual hand within the annotation cubes. We had hoped that the titles printed on the cubes would constrain the distance at which users attempted activation, since they were readable only at close to medium ranges, but this did not deter some students.

The student assessment of the VE system was overwhelmingly positive. Students were asked about their comprehension of the space and the usefulness of the embedded information following their VE session. All of them were able to understand the layout and design of the virtual zoo exhibit through their virtual experience, and they also found it easy to access the embedded information. The students had been to the actual exhibit before using the virtual one, and most commented that they had a better sense of the space after VE usage, because they could travel to viewpoints that are not possible in the actual habitat. Some of the positive response was undoubtedly due to the novelty of virtual reality, but students' test performance revealed the practical effectiveness of the system as well. After the test, one student remarked specifically that she consciously used information from the VE experience when taking the test.

4.3 Results

The results of the evaluation are summarized in Figure 5. None of the differences in test scores shown in the figure are statistically significant, due to the small sample size and a few outlying scores. However, trends found in the results are positive with respect to both of the hypotheses stated above. It is likely that a larger evaluation would produce statistical evidence of both of these claims.

The figure shows both the average and median scores for the entire test and for the three subsets of questions

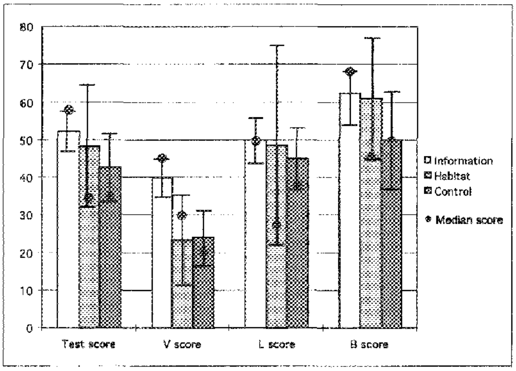

Figure 5. *Summary of average test score results with standard error bars and median scores (V: questions relating to information found only in VE; L: questions relating to information found only in lecture; B: questions relating to information found in both the VE and lecture).*

that we mentioned previously. The information group had the highest average and median score for each of the subsets and the complete test. Median scores are given due to the large effect of a few outliers on the average scores. Note that in all cases, the median score for the information group was equal to or higher than the average, while for the other two groups the median score was equal to or lower than the average in every case but one.

We also collected and analyzed some peripheral data not directly related to performance on the test. First, we wondered whether the time between the use of the VE system and test would have an effect on performance. However, we found no correlation between this time period and test score. Second, we collected data on the number of pieces of information of each type (audio, text, and image) viewed by each member of the information group. These students viewed from 62% to 85% of the total information in the virtual exhibit. However, the information visited did not correlate with test score (or scores) on any of the three subsets of questions. This was also true of the amount of time spent in the virtual exhibit, in both the exploring and information-gathering phases.

Finally, we analyzed the results of a normal in-class test the week following our evaluation, and found that the information group had a slightly higher score than the other two groups. One might conclude that the differences in test scores from our evaluation, then, were due to the fact that the information group as a whole was more intelligent! We calculated the ratio of the experimental test scores to the normal class test scores to check this conclusion. This ratio, on average, was higher for the information group than for the habitat and control groups, suggesting that the information-rich VE did indeed enhance the learning experience.

4.4 Analysis and Discussion

Taking a closer look at the summary statistics from our evaluation, some interesting trends and observations arise. The trends are stronger when we look at the median scores of the groups, because this removes some of the effect of outliers on the average score. However, the trends are visible when average is considered as well. Trends favored both of the hypotheses, though we again stress that differences were not statistically significant, and that further work must be done to prove these claims.

Recall that the first hypothesis was that the VE system paired with a lecture on the same material would provide greater learning and understanding than a lecture alone. Here, it is important that we look at overall performance, as well as the performance of students on those questions that were answered in both the virtual exhibit and the lecture (B questions). Students in the control group had received the information necessary to answer these questions, but the information group students scored higher on these questions. This suggests that the VE produced some absolute educational benefits.

One might say that these benefits occur only because the information group received this information twice (more time spent on task), and that the method of presentation was not the important factor. Even if this is true, it does not negate the hypothesis, which was that an information-rich VE is an effective method of education when paired with traditional classroom teaching. On an intuitive level, it is clear that the VE is not simply a second method of presentation equivalent to another lecture. It is better at exploiting associations between spatial and abstract information, and it adds a strong experiential component to the educational process. The lecture excels at explaining concepts in detail and providing a strong theoretical foundation. The results of the evaluation suggest that together these techniques are more effective than the traditional technique by itself.

Trends also suggest that the students in the information group were better equipped to learn from the lecture due to their VE exposure. One of the most interesting facts in Figure 5 is that the information group scored higher than the other groups on questions that were answered only in the lecture (L score). The difference in averages is not very large, basically due to one high score in both the habitat and control groups, but the difference in the median grade is impressive. This suggests that students who used the information-rich VE were able to draw on that experience during the lecture, creating more and richer mental associations that aided them on the test.

For example, a series of three questions (all in the lecture-only subset) asked students about the tendency of gorillas who had previously been in research labs to remain near the holding building in the back of the exhibit. Students were asked to describe this tendency, why it was a problem from a design point of view, and what changes had been made by the keepers to combat the problem. A student from the information group, listening to this information in the lecture, could visualize the position of the holding building at the back of the exhibit and immediately realize that there was no sight line between the visitor viewing points and this position. When the changes were described (dispensing food from the top of the visitors center instead of near the holding building), this student could also visualize the center and what effect the change would have (gorillas would venture down the hill toward the visitors to get food). Thus, the information group had the opportunity to create mental associations that contained both spatial and symbolic information in a tightly coupled manner. To a limited extent, this is also true of the habitat group, but they were not given the names of the two buildings nor the locations of the visitor viewpoints, so it would be more difficult for them to create the same associations.

We also see from the results that our original assumption—that the information-rich VE alone is not very effective as a teacher—was generally correct. On the questions that could be answered only from the information in the VE, the information group had higher scores, but only approximately 15% higher than students who had not received the information at all. The information group answered only approximately two of five questions correctly on average from this subset. This is lower than their overall average, and is the lowest of the averages of the three subsets of questions.

5 Conclusions and Future Work

In this paper, we have presented an educational, information-rich virtual environment, along with a study suggesting that such VEs, when combined with normal classroom teaching, can produce increases in learning and a richer framework within which to associate spatial and abstract information. This work supports our claim that a VE that includes both spatial and abstract information allows learners to better understand the relationships between the two types of data. This enriched form of learning can be achieved in other ways, such as laboratory work and field trips, but these cannot offer the range of experience that can be produced in a virtual environment, since VEs can be programmed to provide the learner with any conceivable situation and are not limited to the conditions available in the physical world. VEs also allow students to enter environments that are inaccessible because of their scale (a collection of molecules), their distance or cost (the coral reefs off New Zealand), or the danger involved (the inside of the gorilla habitat). However, further work is needed to produce statistical proof of the advantages of information-rich VEs for education.

The virtual zoo exhibit has another component that allows users to make modifications to the design of the habitat by moving trees, changing the terrain, repositioning visitor viewpoints, and so on (Bowman, Wineman, Hodges, & Allison, 1998). The class that participated in our evaluation was later part of a usability study involving these design tools. Each project team created a unique design in which they applied their knowledge of the philosophy of habitat design. Thus, information gathering and constructive learning are integrated into a single system, and students can compare their designs and design rationales to the originals.

In the future, we plan to continue our study of information-rich virtual environments and their application to both education and general information-gathering tasks. New information types and embedding techniques will be needed to create a tighter coupling between information and environment. We will also be studying ways to integrate experiential learning (such as the virtual physics experiments discussed earlier) into information-rich VEs. Finally, we will continue our research into effective and efficient interaction techniques for immersive VEs.

Acknowledgments

The authors wish to thank the students in Dr. Wineman's Psychology of Environmental Design course for their participation in our study. We also acknowledge the help and support of other members of the Virtual Reality Gorilla team: Brian Wills, Kyle Burks, Kristen Lukas, and Lori Perkins, and the support of Zoo Atlanta and its Director and CEO, Dr. Terry Maple.

References

Allison, D., Wills, B., Hodges, L., & Wineman, J. (1997). Gorillas in the Bits. In *Proceedings of the Virtual Reality Annual International Symposium*, 69–76.

Allison, D., Wills, B., Bowman, D., Wineman, J., & Hodges, L. (1997b). The Virtual Reality Gorilla Exhibit. *IEEE Computer Graphics & Applications, 17*(6), 30–38.

Angus, I. & Sowizral, H. (1995). Embedding the 2D Interaction Metaphor in a Real 3D Virtual Environment. In *Proceedings of SPIE, Stereoscopic Displays and Virtual Reality Systems, 2409*, 282–293.

Benford, S., Snowdon, D., & Mariani, J. (1995). Populated Information Terrains: First Steps. In R. Earnshaw, J. Vince, & H. Jones (Eds.), *Virtual Reality Applications* (pp. 27–39). Academic Press.

Bergman, L., Richardson, J., Richardson, D., & Brooks, F. (1993). VIEW—An Exploratory Molecular Visualization System with User-Definable Interaction Sequences. In *Computer Graphics* (Proceedings of SIGGRAPH), 117–126.

Bolter, J., Hodges, L., Meyer, T., & Nichols, A. (1995). Integrating Perceptual and Symbolic Information in VR. *IEEE Computer Graphics and Applications, 15*(4), 8–11.

Bowman, D., Koller, D., & Hodges, L. (1997). Travel in Immersive Virtual Environments: An Evaluation of Viewpoint Motion Control Techniques. In *Proceedings of the Virtual Reality Annual International Symposium*, 45–52.

Bowman, D. & Hodges, L. (1997). An Evaluation of Techniques for Grabbing and Manipulating Remote Objects in Immersive Virtual Environments. In *Proceedings of the Symposium on Interactive 3D Graphics*, 27–30.

Bowman, D. & Hodges, L. (1997). Toolsets for the Development of Highly Interactive and Information-Rich Virtual Environments. *The International Journal of Virtual Reality*, 3(2), 12–20.

Bowman, D., Hodges, L., & Bolter, J. (1998). The Virtual Venue: User-Computer Interaction in an Information-Rich Virtual Environment. *Presence: Teleoperators and Virtual Environments*, 7(5), 478–493.

Bowman, D., Wineman, J., Hodges, L., & Allison, D. (1998). Designing Animal Habitats within an Immersive VE. *IEEE Computer Graphics & Applications, 18*(5), 9–13.

Brelsford, J. (1993). Physics Education in a Virtual Environment. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, 1286–1290.

Brooks, F., Airey, J., Alspaugh, J., & Bell, A. (1992). Final Technical Report: Walkthrough Project. Report to National Science Foundation. (Report No. TR92-026). Chapel Hill, NC: University of North Carolina.

Bryson, S. & Levit, C. (1992). The Virtual Wind Tunnel. *IEEE Computer Graphics and Applications, 12*(4), 25–34.

Coe, J. (1985). Design and Perception: Making the Zoo Experience Real. *Zoo Biology, 4*, 197–208.

Coe, J., & Maple, T. (1987). In Search of Eden: A Brief History of Great Ape Exhibits. In *AAZPA Annual Proceedings*.

Darken, R. & Sibert, J. (1993). A Toolset for Navigation in Virtual Environments. In *Proceedings of User Interface Software and Technology (UIST)*, 157–165.

Dede, C., Salzman, M., & Loftin, R. (1996). ScienceSpace: Virtual Realities for Learning Complex and Abstract Scientific Concepts. In *Proceedings of the Virtual Reality Annual International Symposium*, 246–252.

Dede, C., Salzman, M., Loftin, R., & Ash, K. (1997). Using Virtual Reality Technology to Convey Abstract Scientific Concepts. In M. Jacobsen & R. Kozma (Eds.), *Learning the*

Sciences of the 21st Century: Research, Design, and Implementing Advanced Technology Learning Environments. Lawrence Erlbaum.

Durlach, N., & Mavor, A., (Eds.) (1995). Virtual Reality: Scientific and Technological Challenges. National Academy Press.

Fairchild, K. (1993). Information Management Using Virtual Reality-Based Visualizations. In A. Wexelblat (Ed.), *Virtual Reality Applications and Explorations* (pp. 45–74). Academic Press Professional.

Fairchild, K., Poltrock, S., & Furnas, G. (1988). Semnet: Three-Dimensional Graphic Representations of Large Knowledge Bases. In *Cognitive Science and its Applications for Human-Computer Interaction.* Lawrence Erlbaum Associates.

Hinckley, K., Pausch, R., Proffitt, D., Patten, J., & Kassell, N. (1997). Cooperative Bimanual Action. In *Proceedings of CHI,* 27–34.

Hodges, L., Rothbaum, B., Kooper, R., Opdyke, D., Meyer, T., North, M., de Graff, J., & Williford, J. (1995). Virtual Environments for Treating the Fear of Heights. *IEEE Computer, 28*(7), 27–34.

Kessler, D., Kooper, R., & Hodges, L. (1998). The Simple Virtual Environment Library: Version 2.0 User's Guide. Graphics, Visualization, and Usability Center Technical Report GIT-GVU-98-13.

Laurel, B., Strickland, R., & Tow, R. (1994). Placeholder: Landscape and Narrative in Virtual Environments. *ACM Computer Graphics, 28*(2).

Poupyrev, I., Billinghurst, M., Weghorst, S., & Ichikawa, T. (1996). The Go-Go Interaction Technique: Non-linear Mapping for Direct Manipulation in VR. In *Proceedings of the ACM Symposium on User Interface Software and Technology,* 79–80.

Risch, J., May, R., Thomas, J., & Dowson, S. (1996). Interactive Information Visualization for Exploratory Intelligence Data Analysis. In *Proceedings of the Virtual Reality Annual International Symposium,* 230–238.

Robertson, G., Card, S., & Mackinlay, J. (1993). Information Visualization Using 3D Interactive Animation. *Communications of the ACM, 36*(4), 57–71.

Song, D., & Norman, M. (1993). Cosmic explorer: A Virtual Reality Environment for Exploring Cosmic Data. In *Proceedings of the IEEE Symposium on Research Frontiers in Virtual Reality.*

Tate, D., Sibert, L., & King, T. (1997). Using Virtual Environments to Train Firefighters. *IEEE Computer Graphics & Applications, 17*(6), 23–29.

Wickens, C. (1992). Virtual Reality and Education. In *Proceedings of IEEE International Conference on Systems, Man, and Cybernetics,* 842–847.

Wineman, J., Hodges, L., Allison, D., & Wills, B. (1997). Virtual Gorilla Project: Gorillas in the Bits. *Proceedings of the Ed-Media/Ed-Telecom 97 World Conference.*