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PREFACE

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Background and Purpose

Educating current and future generations of American children to live in an information society is a critical issue. It is compounded by the recognized need to provide life-long education for all citizens and to support a flexible workforce. Virtual reality (VR) technology has been widely proposed as a major technological advance that can offer significant support for such education. There are several ways in which VR technology is expected to facilitate learning. One of its unique capabilities is the ability to allow students to visualize abstract concepts, to observe events at atomic or planetary scales, and to visit environments and interact with events that distance, time, or safety factors make unavailable. The types of activities supported by this capability facilitate current educational thinking that students are better able to master, retain, and generalize new knowledge when they are actively involved in constructing that knowledge in a learning-by-doing situation.

The potential of VR technology for supporting education is widely recognized. Several programs designed to introduce large numbers of students and teachers to the technology have been established, a number of academic institutions have developed research programs to investigate key issues, and some public schools are evaluating the technology. It has already seen practical use in an estimated twenty or more public schools and colleges, and many more have been involved in evaluation or research efforts.

This paper reviews current efforts that are developing, evaluating, or using VR technology in education. It builds a picture of the states of the art and practice, and reviews some of the critical questions that are being addressed. While the coverage of efforts is not intended to be comprehensive, it does provide a representative sampling of recent and current activities. Educational uses of the technology are broadly distinguished as those where students interact with pre-developed VR applications and those where students develop their own virtual worlds in the course of researching, understanding, and demonstrating their grasp of some subject matter.

Pre-developed Educational VR Applications

Over forty efforts in the category of pre-developed applications are reported in this paper. In the majority of these efforts, a single student interacts with the virtual world; although this student may be collaborating with others in his physical classroom, there is no collaboration in the virtual world. Only three of the efforts currently support multiple users, and they provide only very limited types of interaction between users.

Efforts using pre-development applications are almost equally split between those conducted primarily as research efforts and those where VR applications were developed for practical use (although several of the applications developed as part of research efforts are also expected to see eventual practical use). The first practical use of an educational VR application that has been identified occurred in 1993, and some twenty applications are expected to have seen practical use by the end of 1997.

Nearly three-quarters of the applications are immersive, using either a head-mounted display (HMD) or cave display to visually immerse a user in the virtual world. While a few researchers have started to look at the use of spatialized sound and haptic interfaces, these are not in practical use as yet.

Discounting applications intended for use by all age groups, the predeveloped applications are nearly equally split between those designed for elementary and middle school students, for high school students, and for college students (undergraduate and graduate). They cover a broad range of subjects with, again, a fairly equal split between the arts/humanities and sciences. A few are designed to meet specific country or state learning objectives. The majority support constructivist learning using an experiential or guided-inquiry paradigm. Several applications are being developed to meet the special needs of students with learning disabilities, autism, or certain physical disabilities.

Student Development of Virtual Worlds

More than twenty efforts are reported in the category of student development of virtual worlds. Here, nearly two-thirds of the efforts have been conducted as a practical part of the curriculum and the remainder, while also conducted in classrooms, are primarily regarded as research activities. The first identified practical effort was undertaken in 1993, and students will have been involved in at least twelve different virtual world building efforts by the end of 1997. Although a few of these efforts have been, or are intended to be, repeated on a regular basis, most have been one-time events.

The efforts are equally split in their use of either a desktop or immersive VR system, although the practical uses have largely entailed the development of desktop virtual worlds, whereas the research activities have focused on student development of immersive worlds. Most of the worlds have been developed by students working in groups. While these students have needed little technical support for desktop world development activities, students have been actively supported by researchers in the development of immersive worlds.

For this category, the majority of efforts are being conducted at the middle school level, with more efforts at this educational level than at elementary school, high school, and college levels combined. While these efforts address a smaller number of subjects than the pre-development applications, the range is still extensive.

Evaluations

In total, thirty-five evaluations on the identified efforts have been completed. An additional twenty evaluations are currently underway or already planned. Just as the majority of educational uses of VR technology have involved pre-developed applications, so have the majority of evaluations to date been performed on this category of applications. All efforts in the categories of pre-developed applications and student world development that are classified as research-oriented have been the subject of at least one evaluation. But while over half of the pre-developed applications in practical use have been evaluated, only two of the eleven practical-use efforts where students have developed their own virtual worlds have seen a similar type of evaluation. While these figures seem low, it must be remembered that all current educational uses of VR technology are, at least to some extent, exploratory, and even when no explicit evaluations have been performed, the researchers and teachers are forming their own opinions of the value of the technology.

Given this level of activity, what has been learned about the effectiveness and usability of the technology? Although the current data is insufficient for any substantive conclusions to be drawn, some initial findings can be posited:

- *Use of both pre-developed VR applications and student development of virtual worlds can be educationally effective.* All studies that have investigated whether students using VR technology could meet stated learning objectives found that some level of learning does occur. However, the extent of such learning has varied. The few formal studies (two for pre-developed applications and three for student-development efforts) that have examined whether VR technology provides a more effective learning tool than traditional classroom practices have shown that students using VR technology performed at least equivalently and usually better than those using other forms of instruction. Other studies have shown that while immersive applications have been more effective than non-immersive applications, the key factor seems to be the interactivity of these applications rather than the fact of immersion.
- *Students enjoy working with virtual worlds and this experience can be highly motivating.* Reports of student enjoyment are common and several researchers and teachers report striking improvements in student motivation. Surprisingly, students are very tolerant of the low resolution and cumbersomeness of current HMDs. The main problem seems to lie in navigating around the worlds. Occurrences of simulator sickness symptoms are rare, and symptoms that do occur take the form of disorientation and ocular discomfort, and not nausea.

- *Teachers report their role in the classroom changing*. Instead of being a teacher with all the answers, teacher have found themselves acting as facilitators who support students in their discovery of worlds and in their building ideas based on information gained from those worlds. The use of pre-developed applications, however, can pose a problem for lesson administration and monitoring students' progress.
- *In practical terms, desktop VR is more suitable for widespread use than immersive VR technology.* Considering both the hardware and software requirements, desktop VR is quite a mature technology. It is affordable in that a basic level of technology can be achieved on most existing personal computers at either no cost or some minimal software cost. The expected availability of increasing numbers of virtual worlds over the Web is likely to promote its use. While immersive VR is being used in several practical applications, this part of the technology is less mature, with shortcomings in such areas as displays, system lag, and common interaction metaphors. Immersive VR is also expensive, with a single hardware/software platform (including HMD and other specialized interface devices) starting at around $15,000. An unstable marketplace is likely to slow the widespread use of immersive VR technology.

At this time, there is no data to support findings on the effectiveness of the technology for collaborative learning, or the cost-effectiveness of VR-based education.

Concluding Remarks

It is important to note that current uses of the technology tend to be isolated examples of what proponents of the technology can achieve. Moreover, almost exclusively, the studies have concerned one-time use of virtual worlds and there is no information on how students respond to the technology over the long term. Additional work is required to substantiate or refine current findings and to answer specific questions, such as which characteristics of the technology support particular types of learning and how use of the technology should be integrated with other educational activities.

Existing data does suggest that this technology offers significant, positive support for education. It indicates sufficient potential value to justify continuing research and development activities and increasing practical evaluations of technology uses. Such work needs to occur hand-in-hand with research into constructivist and collaborative learning. Thought must also be given to how to train teachers in the use of the technology.

1. Introduction

The purpose of this paper is to report on educational uses of virtual reality (VR) technology. By presenting examples of both systems that are in practical use and those that are still the subject of research and development, it provides a sense of the current state of the practice and the state of the art. The paper also looks at researchers' and teachers' evaluations of VR educational applications to see what has been learned, how critical questions are being answered, and whether the technology is starting to live up to its promise.

1.1 Background

Many researchers and educational practitioners believe that VR technology offers strong benefits that can support education. For some, VR's ability to facilitate constructivist learning activities is the key issue. Others focus on the potential to provide alternative forms of learning that can support different types of learners, such as visually oriented learners. Still others see the ability for learners, and educators, to collaborate in a virtual class that transcends geographical boundaries as the major benefit.

In traditional instructional environments, students are expected to learn by assimilation, for example, by listening to an instructor lecture about a subject. Current educational thinking is that students are better able to master, retain, and generalize new knowledge when they are actively involved in constructing that knowledge in a learning-by-doing situation. This is a philosophy of pedagogy called *constructivism* and its supporters vary, ranging from those who see it as a useful complement to teaching-by-telling to those who argue that the whole curriculum should be reinvented by students through gently guided discovery learning [Dede 1997a].

As noted by Jonassen [1994], the major distinction between traditional instructional design and constructivism is that the former focuses on designing instruction that has predictable outcomes and intervenes during instruction to map a predetermined conception of reality onto the student's knowledge, while the latter focuses on instruction that fosters the learning process instead of controlling it. Jonassen also points out that constructivists focus on learning environments rather than instructional sequences, recommending features such as those identified in Figure 1.

The support VR technology provides for constructivist learning is discussed in some detail by Winn [1993]. Winn suggests that immersive VR technology allows three kinds of knowledge-building experiences that are not available in the real world, but that are important for learning. These pertain to *size*, *transduction*, and *reification*. VR technology allows radical changes in the relative sizes of the student and virtual objects. Using Winn's examples, at one extreme, a student could enter an atom and examine and adjust electrons in their orbitals, thus altering the atom's valence and its ability to combine to form molecules; or at the other extreme, a student could acquire a sense of the relative sizes and distances in the solar system by flying between planets. Transduction refers to the use of interface devices to present information that is not readily available to human senses. For example, variations in the intensity of some sound could be used to portray levels of radiation, or color could be used to show the movement of oxygen through an environment. Together, transduction and the ability to manipulate size support reification, which is the process of creating perceptible representations of objects and events that have no physical form, such as mathematical equations.

VR worlds can also be used to circumvent the physical, safety, and cost constraints that limit schools in the types of environments they can provide for learning-by-doing. For example, it would be impractical to allow students studying chemical engineering to further their understanding of the underlying processes by conducting experiments with the equipment at an operating chemical production plant. This type of activity can be performed in a virtual world. As this example hints, VR learning environments can also support the notion of *situated learning* where students learn while in the actual context where that learning is to be applied.

- Provide multiple representations of reality, thereby avoiding oversimplification of instruction and representing the natural complexity of the real world;
- Focus on knowledge construction, not reproduction;
- Present authentic tasks (contextualizing rather than abstracting instruction);
- Foster reflective practice;
- Enable context- and content-dependent knowledge construction; and
- Support collaborative construction of knowledge through social negotiation, not competition among learners for recognition.

(Based on Jonassen [1994].)

Figure 1. Constructivist Learning Environments

Within the constructivist philosophy, various actual pedagogical approaches can be taken. The most popular pedagogical approach is one of guided-inquiry where, by performing tasks such as experiments, students are guided to uncover critical concepts for themselves. An experiential approach is the second most common approach. While all virtual worlds allow a user to experience a virtual situation, the term "experiential" is used in this paper to refer to more than simple walkthroughs of a virtual world. Instead, educational VR applications described as experiential require some further interaction on behalf of the student.

VR technology also can provide a different framework for education, one that is independent of a physical classroom and the restrictions levied by the availability of educational resources at any one physical location. In this context, the term "virtual classroom" is used to imply more than the use of telecommunications technologies to provide an electronic simulation of a conventional classroom, although this can have merit of its own (see [Turoff

1995]). Instead, as best discussed by Tiffin and Rajasingham[1] [1995], the concept of a virtual classroom embodies a new paradigm of learner-centered education suitable for lifelong learning. In this paradigm, students of all ages participate in educational activities from their home, place of work, or some type of "school house." Students shape their own curriculum to meet their personal needs, joining classes appropriate to their learning objectives that are given in venues suited to the topics of interest. Classes are not limited to the availability of appropriate teachers in the region but can meet at a time convenient to all participants, independent of the geographical locations of those participants. Access to libraries, laboratories, and other educational resources is not limited to certain hours but available round the clock.

This utopian view has some very real education control and social issues to contend with, particularly for young students, and would require major rethinking and restructuring of the educational system. Such changes are is unlikely to occur any time soon, if indeed this is the right educational approach to take. Research on virtual classrooms is starting at three or four sites internationally but due to the preliminary nature of this work, these efforts are not discussed in this paper.

1.2 Approach

Educational uses of VR technology were identified by several means. Some uses were already known to the author, others were identified by colleagues, or found mentioned in the open literature or Web sites. As particular efforts were identified, the educators or researchers involved were contacted for more information about their work.[2] In addition to collecting detailed, factual data about each usage, information was sought that would allow investigating critical issues about using VR technology for education.

To help clarify these issues and provide some type of yardstick by which progress can be measured, several high-level questions were formed. Some of the most obvious questions relate to effectiveness of VR-based education, namely:

- Does learning in virtual worlds provide something valuable that is not otherwise available?
- How does the effectiveness of student use of pre-developed virtual worlds compare with traditional instructional practices?
- How does the effectiveness of student development of virtual worlds compare with other instructional practices?

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[1] These authors prefer the term "virtual learning space" to avoid the suggestion that a virtual class is held in an electronic version of a conventional classroom. The more common term "virtual classroom" is used here.

[2] Exceptions are the teacher at H.B. Sugg Elementary School who conducted a study with student development of virtual pyramids, and the researcher at Oregon State University who looked at the use of VR for promoting awareness of spatial relations.

- How does the effectiveness of student use of pre-developed virtual worlds compare with that of student development of virtual worlds?
- How does the effectiveness of immersive and non-immersive virtual worlds compare?
- How well does VR technology support collaborative learning between students? Is this collaboration educationally effective?
- Is VR-supported learning cost effective?

A closely related issue concerns where VR technology should and, equally important, should not be used. Questions here address both educational content and student characteristics:

- For what type of educational objectives or material is VR technology best suited? Where is it not suited?
- Are there specific student characteristics that indicate whether VR-based education is appropriate? Does the technology benefit only certain categories of students?

Potential student and teacher acceptance of VR learning environments will depend on many factors, including ease of interface use, and ease of integration into the classroom.

- Do students find VR interfaces easy to work with?
- Does the effective use of VR technology change the teacher's role in the classroom?
- What are student and teacher reactions to the use of this technology?

Practical questions that need to be considered are:

- Are the hardware platforms and minimum set of interface devices required affordable to most schools?
- Are the needed software development tools commonly available?
- Is the technology currently mature enough for practical use?

These questions will be revisited at the end of this paper. While the information presented in the paper is insufficient to provide definitive answers, it is does provide some useful indicators of current trends and problem areas.

1.3 Scope

In this paper, the term "virtual reality" is used broadly to cover both immersive and non-immersive VR. The sense that a user is actually present in a virtual environment is termed "presence" and is an artifact of being visually immersed in the computer-generated virtual world. Presence is often held to be the discriminating feature of VR applications. This view would exclude from consideration non-immersive VR applications, that is, those that rely on a traditional desktop monitor or single projection screen for the display. At this stage in the development of the technology this restriction may be a mistake, at least for the educational uses discussed here. Although the cost of the special systems needed for immersive VR is coming down, these systems are still beyond the scope of most school budgets. Also, there are unresolved questions relating to health and safety issues that arise in the use of immersive systems [Wilson 1996]. Moreover, there is no overwhelmingly conclusive evidence that immersive systems are more effective in educational applications than their non-immersive counterparts. Omitting non-immersive applications would mean ignoring many promising efforts that have valuable information to offer. Accordingly, this paper addressed educational uses of both immersive and non-immersive VR.

The scope of the study reported here is limited to educational uses of VR technology and excludes training applications. In other words, the focus was restricted to those applications intended to impart knowledge; not considered were applications designed to provide for the development and practice of work-related skills. The study was further limited to consideration of only graphical VR applications, ignoring their textual counterparts referred to as Multi-User Domains or Dungeons (MUDs) or object-oriented MUDs (MOOs). Also, it is not concerned with those instances where VR technology itself is being taught, but rather where VR technology is used as the learning medium. Within this context, the paper provides information on VR applications designed to teach particular topics, and those cases where students are themselves developing virtual worlds. As such, it covers kindergarten through grade 12 (K-12), college, and other educational venues.

1.4 Organization of Paper

Section 2 provides an overview of efforts designed to provide educators and students with a basic appreciation of the potential of VR technology. In Section 3, specific educational uses of VR are summarized and discussed. While the coverage of existing and planned work is by no means comprehensive, a representative set of uses of the technology is covered. Section 4 focuses on evaluations that are underway or have been completed. These evaluations include experiments comparing the educational effectiveness of VR applications with traditional learning practices. Section 5 reviews the questions just raised with respect to what has been learned and provides some remarks on the status of VR in education and critical research needs.

The names and locations of those researchers and teachers who participated in this study are given in Appendix A. The paper concludes with a list of references and a list of acronyms used.

2. Introductory Programs

The section provides an overview of some programs that are intended to provide a basic appreciation of educational applications of VR technology. These programs are listed in Table 1, along with identification of the group that provides the program and the funding organization. As can be seen in this table, various schools, colleges, state organizations, and government agencies are all playing a role in promoting the use of VR technology in education. The goals of the programs range from providing students with the opportunity to visit virtual worlds, to placing VR software in the hands of teachers who will use it to meet their specific teaching objectives in the classroom.

Table 1. Programs Introducing the Educational Potential of VR Technology

	Program Name	Provided By	Participants	Date
Outreach	Virtual Reality Roving Vehicle (VRRV)/Washington	University of Washington, Human Interface Technology Laboratory (HITL), Seattle, WA	Teachers and students grades 4-12	1994-1997
	VRRV/Nebraska, Phase I and II	Education Service Unit #3 of Nebraska, Educational Development Center, Omaha, NE	Teachers and students	1995 onward
	Mobile Aeronautics Education Laboratory (MAEL)	NASA/Lewis Research Center, Cleveland, OH	Students grades 9-12	1997 onward
Web	—	University of Washington, HITL	Teachers	1996 onward
Teacher Education	VRRV/Nebraska, Phase III	Education Service Unit #3 of Nebraska, Educational Development Center	Teachers	1997 onward
	Educators' VR Series	Haywood Community College, Regional High Tech Center, Waynesville, NC	Teachers	1994 onward
	Virtual Reality in the Schools	East Carolina University, Virtual Reality and Education Laboratory (VREL), Greenville, NC	Teachers	1995 onward
	Virtual Education - Science and Math of Texas (VESAMOTEX)	Slaton Independent School District, Wilson, TX	Teachers	1995-1997
	VR Concentration, M.A. in Education	East Carolina University, VREL	Teachers	1996 onward
Collaborative	VR in Education	University of Illinois, National Center for Supercomputing Applications (NCSA), Champaign, IL	Teachers	1996-1997
	Virtual Reality in the Schools	East Carolina University, VREL	Teachers	1995 onward

2.1 Outreach Programs

Looking first at the outreach programs that have taken VR systems to elementary, middle, and high schools, there are three programs to consider:

- Virtual Reality Roving Vehicles (VRRV)/Washington,
- VRRV/Nebraska, Phases I and II, and
- Mobile Aeronautics Education Laboratory (MAEL).

The VRRV programs have had the largest impact to date, using vans to bring VR to over 7,000 students and educators. VRRV/Washington was the first outreach program to start. It was conducted in two phases. The initial phase, called the Hors d'Oeuvre, provided participants at various schools with presentations on VR technology and the opportunity to visit virtual worlds. Researchers visited schools for one day or more to present and discuss VR, and then provide a demonstration of commercially developed virtual worlds. The second phase, called the Entrée, provided a more in-depth introduction to the technology by supporting students. In this case, researchers spent several days with teachers and students who, over a period of several weeks, developed their own virtual worlds on topics such as Wetlands Ecology and Global Warming (these worlds are discussed in Section 3.2).

The first phase of VRRV/Nebraska was modeled after VRRV/Washington's Hors d'Oeuvre. The second phase differed from VRRV/Washington, however, by supporting teachers in a one-week intensive effort where they were able to use the University of Washington Human Interface Technology Laboratory (HITL)-developed Atom World to teach atomic and molecular structures or, alternatively, choose their own approach for using VR technology to support their curriculum. VRRV/Washington and the outreach parts of VRRV/Nebraska have been sponsored by the US West Foundation. They have now come to an end, although analysis of collected data continues.

The third outreach program, MAEL, is just getting underway. Unlike the VRRV programs, VR is only one of the educational tools demonstrated by MAEL. Using a 16-wheeler truck for transportation, this program uses ten different types of workstations to teach students about aeronautics, mathematics, and science. The immersive VR workstation provides a virtual biplane that student use to explore aeronautical concepts. MAEL is intended to be used in two ways: as an exhibit at air shows and other public aeronautic events, and as an educational tool designed to visit schools and provide students with access to a predefined (or custom) curriculum. MAEL began its first trip in January 1997, visiting schools near the National Aeronautics and Space Administration (NASA) Ames Research Center and the NASA Dryden Flight Research Center. It is expected to spend six months a year on the road for the next several years. The feasibility of setting up permanent versions of the MAEL components at various schools, colleges, and science centers is being investigated.

In addition to exposing students and teachers to the potential of VR technology, these three programs also have a research element. One of the goals of the Hors d'Oeuvre phase in the VRRV programs was to determine the limitations and potential uses of VR technology for education. With respect to the Entrée phase, the researchers assessed whether having students build their own VR worlds helped them understand the concepts and principles they were learning as part of the regular curriculum. The results from these evaluations are reported in, respectively, Section 4.1 and Section 4.2. The research agenda of MAEL with respect to the VR part of its program includes two fronts. The first of these is looking at students' reactions to a virtual flight experience. The second is more opened ended and based on the use of video cameras to record students' interactions with the VR workstation. The recordings will be used to help refine the curriculum and educational programs and also to provide data for outside researchers studying how students learn using advanced technology teaching methods. It is too early for this program to have any results to report.

2.2 Web-Based Programs

Another type of program is illustrative of the great variety of roles that the Web offers. Based on the understanding of educational VR applications they gained through the VRRV program, the HITL has increased the VR resources available to teachers by providing a Web site intended to make teachers aware of the use of VR technology in education. Currently, this site provides some introductory information about VR and brief guidance on world building using the Global Change application (see Section 3.1) as a model. A Virtual Reality Modeling Language (VRML) version of this world is available for downloading. This effort has been sponsored by the U.S. Department of Education, Funds for Innovation, Teacher/Pathfinder program. Should additional funding become available, the HITL might provide additional resources in the form of on-line teacher support.

2.3 Teacher Education Programs

There are five programs that provide some type of education for teachers regarding the use of VR technology. Together, these programs have introduced over 100 teachers from public school systems, colleges, and universities to VR technology. The programs are:

- VRRV/Nebraska, Phase III,
- Educators' VR Series,
- Virtual Reality in the Schools,
- Virtual Education - Science and Math of Texas (VESAMOTEX), and
- VR Concentration, M.A. in Education.

The third phase of VRRV/Nebraska is just starting and its goal is to prepare and support teachers in the use of VR for constructivist learning activities based on the desktop computing facilities schools already have available. To this end, Education Service Unit #3 of Nebraska offers one-day workshops for educators and is expected, in some cases, to work directly with teachers on special projects.

The first offering of the Educators' VR Series program was a one-day workshop given with support from Autodesk Applied Software. More recently, a one-week workshop was provided at the request of the North Carolina Center for the Advancement of Teaching. In the summer of 1997, Haywood Community College plans to offer its first VR Summer Institute for Educators.

The Virtual Reality in the Schools program offers an annual multi-day workshop for teachers who are interested in learning about VR technology. This program provides further support for teachers through its quarterly journal publication entitled *VR in the Schools*. This journal provides updates on the Virtual Reality and Schools project, as well as reports on relevant studies and current practical uses of the technology, reviews of VR-related software and hardware, and general articles of interest. VREL also provides a number of pamphlets discussing VR and education that provide high-level guidance for using VR in the classroom.

The VESAMOTEX program has two objectives: to promote the use of VR in education and to bring VR into practical use to support science education at Slaton High School. In support of the first of these objectives, several presentations have been given on the topics of VR and the VRML to groups such as the Texas Association of Physics Teachers and the Texas Computer Educators Association. Future plans include a discussion in one of the electronic meeting rooms on the Web, where researchers working with VR will be invited to answer questions posed by educators. (The efforts where VR technology has been used in the classroom at Slaton High School are discussed in Section 3.2.) VESAMOTEX is supported by the Texas 1995 Christa McAuliffe Fellowship.

The remaining type of program, and seemingly the only one of its kind at the moment, is VREL's VR Concentration in its Master of Arts in Education (Instructional Technology Specialist-Computer) degree course. Four different courses are offered, with the goal of educating future teachers in the use of VR technology. These courses cover topics ranging from evaluating VR hardware devices and software development tools, to considering ethical implications in educational uses of the technology. One course, EDTC 6242, for example, requires students to work with a local school to develop a VR application that meets specific curriculum objectives, to develop supporting instructional materials for teachers, and then conduct classroom evaluations of the effectiveness of the application they have developed.

2.4 Collaborative Programs

The VR in Education program is part of the National Science Foundation's (NSF) Resource for Science Education program at the National Center for Supercomputing Applications

(NCSA) at the University of Illinois. The purpose of the program is to engage practicing teachers in the VR research community and to improve the understanding of educational issues relating to VR in the classroom. The overall approach of the program is to:

- Partner with a nationally selected, diverse group of educators in a year-long VR and education program,
- Work with educators to help design and test VR systems and applications for use in classrooms at a variety of levels,
- Encourage educators to interact and form collaborations with NCSA staff and scientists on projects applicable to their classrooms,
- Support educators for peer training, sharing of materials, and grant writing, and
- Pay attention to teacher feedback.

Nine teachers from across the country have made a one-year agreement to collaborate with NCSA staff in integrating VR into classroom curricula. These selected participants teach students ranging from kindergarten up through junior college. A series of workshops has provided the teachers with an introduction to various VR hardware and VRML, together with presentations and demonstrations of uses of the technology. During the course of these activities, the teachers and NCSA researchers have collaborated in rating some existing VR applications according to National Science Education Standards, and the group has worked on creating a vision for the use of VR technology in the nation's schools. Additionally, all of the teachers have been using the technology in their classrooms. For example, at Urbana High School, Chicago, IL VR technology is being used in a physics class to help students understand equipotential surfaces. (Details on the ongoing activities and results of the program were unavailable prior to release of a forthcoming NSF/North Central Regional Educational Laboratory (NCREL) report.)

The Virtual Reality in the Schools program also provides direct support for the introduction of VR technology into the classroom. Here, Virtual Reality and Education Laboratory (VREL) staff work with individual teachers who have volunteered to join the project. These teachers are given a copy of either a PC or Mac version of VR development software (Virtus WalkThrough) and provided with hands-on training in its use. VREL staff members then work with the teacher to help identify where VR can best be used in a particular area of the curriculum taught by the teacher. Usually, this collaboration involves selecting specific items from the North Carolina Competency-Based Curriculum Objectives and discussing how VR might be used as a means of student attainment or as a measure of attainment. Once the teacher has designed the lessons that will use VR as a teaching tool, VREL staff continue to be available for consulting and visits to the school. They also help with evaluating success in meeting the specified curriculum objectives. Up to the fall of 1996, seventeen teachers were signed up on this program.

3. Current and Planned Uses of VR Technology

The majority of educational uses of VR technology has involved student use of pre-developed VR applications where students individually visit a virtual world to learn some basic concepts or, for example, to develop an understanding of different periods in history. Alternatively, students may be required to develop their own virtual world to guide the research, understanding, and demonstration of their grasp of scientific or non-scientific material. Uses of VR in these two categories are discussed separately in Section 3.1 and Section 3.2. Multiuser, distributed VR applications are discussed in Section 3.3.

It is interesting to briefly look at the proportions of uses in each of the three categories of pre-developed, student-developed, and multiuser VR. The ratio is, roughly, 13:7:1, with 40 pre-developed applications, 21 student-development efforts, and 3 multiuser applications. The predominance of uses of pre-developed VR applications should not be surprising since these applications provide a good first step for teachers and students in building their understanding of the technology, and a more controllable venue for investigating basic questions pertaining to educational uses of VR technology. Indeed, over half of the efforts in this category are primarily research oriented. Given this fact, and considering the mastery of the technology needed, the relatively large proportion of efforts involving student-development of virtual worlds does, initially, seem somewhat surprising. In fact, the high number of efforts in this category is attributable to the work of just two organizations that, between them, account for nearly two-thirds of the cases.

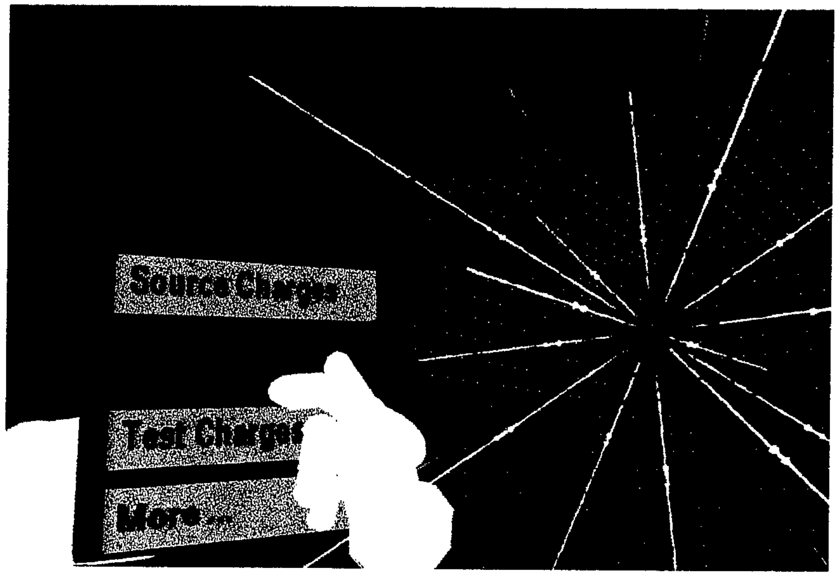
The low number of uses of multiuser, distributed VR reflects the maturity of VR technology itself: the integration of VR, networking, and telecommunication technologies is still in the initial stages of research. Although only three of the efforts discussed here currently fall into this category, several of the developers of pre-developed VR applications have stated their intention to develop multiuser, distributed versions of their current applications at some point in the future.

3.1 Student Use of Pre-Developed Virtual Worlds

In an effort to start by demonstrating the range of applications in this category, Figure 2 and Figure 3 and provide descriptive overviews of two example applications. The selection of these particular applications over any others is not intended to imply "best-in-class," though both are examples of excellent work. The first application, MaxwellWorld, provides an example of an

Project Goal: Examine whether VR's sensorial immersion can help students remediate deeply rooted misconceptions and construct accurate mental models of abstract science concepts.

Focus of Current and Planned Work:
- Extend explorations on how multisensory immersion influences learning.
- Investigate impact of frames of reference on learning.
- Experiment with collaborative learning among geographically remote users inhabiting a shared virtual context.



MaxwellWorld Description: Students build 3D electric fields and explore forces and energy by directly manipulating multiple 3D representations (test charges, field lines, equipotential surfaces, and flux surfaces). They can see, hear, and feel the distribution of forces and energy throughout the space. The field space in the virtual world occupies a 1-meter cube with Cartesian axes display for easy reference. Interaction is achieved via menus and a virtual hand. Menus are attached to a user's wrist so they can be removed from the visual field but are immediately accessible. The virtual hand is used to point to menu items, and a button on a Polhemus 3Ball device is used to make a selection. The hand also allows a student to place positive and negative charges of various relative magnitudes by, for example, attaching a test charge to the tip of the virtual hand. Once a charge configuration has been placed, the force on a positive test can be attached to the virtual hand so that students can see the line(s) of force extending through that point; or the tip of the virtual hand can become a "potential" meter for exploration of the distribution of potential in the world. Gaussian surfaces can also be placed using the virtual hand. Electric field lines, potentials, surfaces of equipotential, and lines of electric flux through surfaces can be instantiated using the menus, and then observed and controlled interactively.

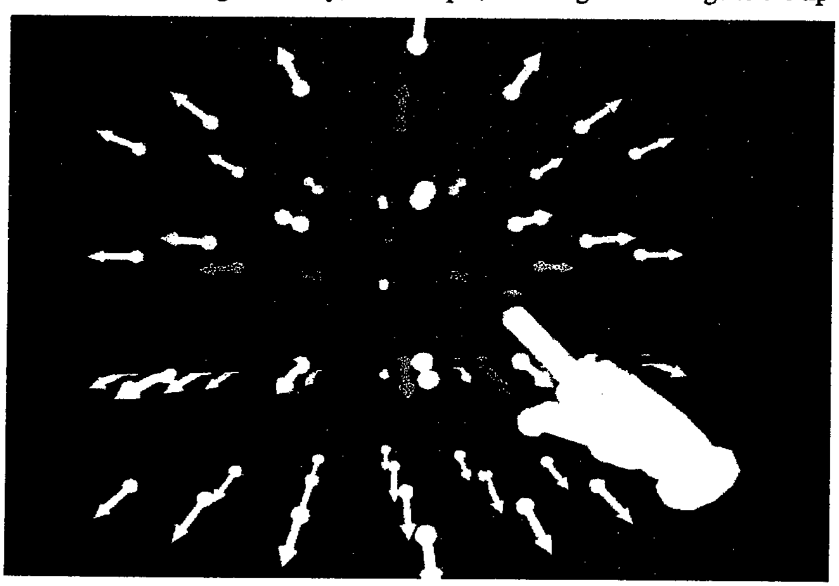
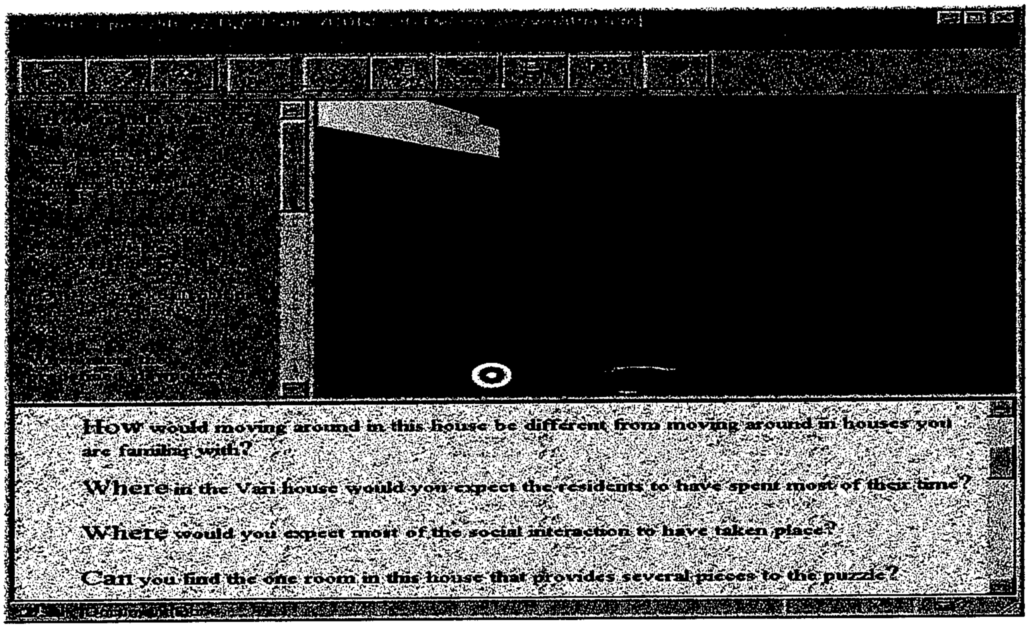


Figure 2. MaxwellWorld

Project Goal: To integrate archaeological data with advanced computer graphics techniques to support education, data analysis, and the preservation of cultural heritage information.

Focus of Current Work: Field testing.



Vari House Description: Two linked virtual worlds show the Vari site as excavated and the Vari house as reconstructed by archaeologists. Links are also provided to supplemental information about Greece and the Vari region. The reconstructed house shows both the exterior and interior of the building and a floor plan is included. Students are guided in the exploration of the worlds by answering questions that help develop critical thinking skills.

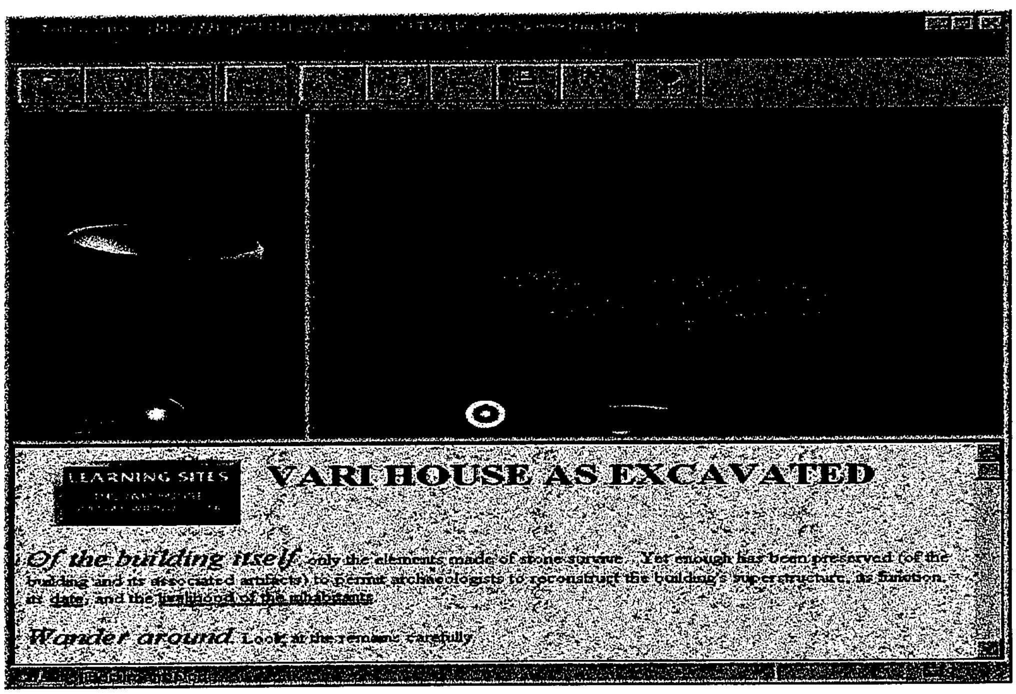


Figure 3. Vari House

application developed as a research tool that runs on high-end machines and provides a fully immersive and multisensory interface. The second application, Vari House, is an example of a professionally-developed desktop product that was designed for practical use and is supported by extensive teaching materials.

Though providing insight into the types of virtual worlds being developed, these two examples are a small subset of current applications. Table 2[3] provides summary details for all the pre-developed VR applications that are considered here. These applications vary greatly in the educational topics supported, their pedagogical approaches, the support they provide for students with special needs, and the type of hardware and software platforms required. These topics are all discussed later. First, however, the different ways in which pre-developed applications are being used is discussed.

3.1.1 Type of Use

Pre-developed VR applications can be broadly distinguished as those developed for practical classroom and exhibition use, and those intended primarily for use as research vehicles. The applications are nearly equally split between these two groups, as shown in Table 3. Some applications in research category may eventually end up in practical use, but this result is not seen as the major purpose for their development.

Table 3. Classification of Applications

Practical Classroom and Exhibition Use	
Virtual Egyptian Temple	Gebel Barkal: Temple B700
Virtual Bicycle	Vari House
Virtual Pompeii	Science Education World
Classical Buildings[a]	Energy Conservation
O'Connor World	Vicher (I and II)
Updike World	Safety World
Nursing World	Map Interpretation World
Milling Machine	3D Map World
VESL	Makaton World
Virtual Biplane	Life Skills World
Research Vehicles	
Cell Biology	Greek Villa
Virtual Gorilla Exhibit	NewtonWorld
CDS	MaxwellWorld
Room World	PaulingWorld
Great Pyramid[a]	AVATAR House
3D Letter World	Phase World
Street World	Atom World
Object World	Global Change
Crossing Streets	Zengo Sayu
LAKE	VRRV Hors d'Oeuvre
Spatial Relations World	

a. Part of Virtus Corporation Archeological Gallery.

For those applications reported here, the first practical classroom use occurred in 1993. The two applications that came into use that year were both designed for learning-disabled students. Two years later, 1995 saw four more applications come into practical use and, since then there has been a small but steady increase in practical usage. By the end of 1997, a total of 17 applications are expected to become part of regular classroom activities. In the case of exhibitions, two applications were made available to the public for short periods in 1995, each at two different venues. Depending on completion of construction at Zoo Atlanta in Georgia, and on the necessary funding for equipment, the Virtual Gorilla Exhibit is expected to become a permanent exhibit at Zoo Atlanta starting in fall 1997.

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3 In this and all subsequent tables, italics are used to denote planned activities.

Table 2. Characteristics and Usage of Pre-Developed VR Applications

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
Carnegie Mellon University, SIMLAB, Pittsburg, PA	Virtual Egyptian Temple	Walkthrough of an Egyptian temple modeled on surviving remains of 2 ancient temples. User can walk through the temple compound where wall paintings come alive and a priest avatar serves as a guide. Supported by 25 hours of reference material on CD-ROM.	Understanding of Greek culture.	Middle - High School	Desktop	*Practical use*	*Commercially available, 1998 (productized by Mind Experience Technologies, Campbell, CA)*	
	Virtual Bicycle	Using a bicycle mounted on a motion platform, user controls speed of bicycling through conditions such as varying road surface. The user encounters several accident scenarios. A skill monitor scores performance and, for low skill levels, an agent offers information and guidance.	Train and rehabilitate young bicycle users.	5-15 years	Projection screens (3)	*Practical use*	*Schools throughout USA*	*2000 onward*
	Virtual Pompeii	Walkthrough of a replication of the Theatre Complex of Pompeii prior to the eruption of Mt. Vesuvius (A.D. 79), showing historical details taken from literary sources such as Pliny (the elder) and historical diggings. The world includes the Large Theater, the Temple of Hercules, and the Triangular Forum. A re-enactment of a typical theatrical performance is provided.	Provide insight into Pompeiian life and culture.	All ages	All forms of display	Exhibition	SIGGRAPH '95	Fall 1995
						Exhibition	DeYoung Museum (San Francisco, CA)	Fall 1995
						Exhibition	*Smithsonian Castle (Washington, DC)*	*Summer 1997*
Correspondence School (NZ)	Classical Buildings	Walkthrough of a depiction of ancient Greek and Roman buildings, and other large-scale artifacts such as roads and aqueducts.	Course: Classical Studies GL 200.	High school, college	Desktop	Practical (optional part of course)	Correspondence School, Wellington, NZ	Mid-1997 onward

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
ERG Engineering, Inc.	Cell Biology	Room where a sick child asks for cells (neuron, muscle cell, intestinal cell) so that he can think, move, and eat. The user builds these cells from different types of organells. He can use help books associated with each self-explaining object or proceed by experimentation. Additional explanations are given as correct/ incorrect organells are added to a cell. Animations show completed cell function.	"Hands-on" experience with the principles of human cell biology.	All ages	HMD (stereo)	Evaluation of impact of immersion and interactivity	The Computer Museum, Boston, MA	March-June 1995
						Exhibition	The Computer Museum, Boston, MA	July 1995
						Exhibition	TEPIA Center, Tokyo, Japan	October-November 1995
Georgia Institute of Technology, Graphics Visualization & Usability (GVU) Center,	Virtual Gorilla Exhibit	User explores a depiction of the Gorilla Exhibit at Zoo Atlanta, including 4 viewable gorilla habitats and the Gorillas on the Cameroon Interpretive Center. By assuming the role of a member of a virtual gorilla family (silverback, adult male and female, juvenile, or infant), the user can test behaviors and elicit responses reflecting his position in the family hierarchy. (Extensions will address animal husbandry and conservation.)	Instruction in (1) gorilla behaviors and social interactions in a family group; and (2) zoo habitat design and layout issues.	K-12	HMD (mono)	Formative evaluation (conducted at Zoo Atlanta)	Midway and Slaton Elementary Schools, Westminster School, Trickum Middle School, Fayetteville High School	Spring 1996
						Exhibition	SIGGRAPH '96, New Orleans, GA	August 1996
						Exhibition	*Zoo Atlanta, Georgia*	*Fall 1997 onward*
	Conceptual Design Space (CDS)	CDS allows students to create, walkthrough, and modify architectural designs while getting immediate feedback on the impact of changes to the architectural space. These designs can be imported from a CAD system or developed from inside the VE. Design tools support, for example, creating simple shapes; modifying and grouping them; and applying simple geometric transformations. A transformation widget supports large-scale object manipulation while detailed manipulations use menus.	ARCH 4613: Advanced Design Studio VI.	College students, architects	HMD (mono)	Comparative evaluation of immersive design and user interface tools	Georgia Institute of Technology	Spring 1995
						Practical use	Georgia Institute of Technology	Winter/ spring 1995
							Lord, Aeck, and Sargent, Inc., Atlanta, Georgia	Winter/ spring 1995

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
Haywood Community College	O'Conner World	Walkthrough of scene from O'Connell's *A Good Man is Hard to Find* to identify objects or conditions that do not belong, are important to the scene, or missing.	ENG 254: Major American Writers, English 277: Exploring Literature Through Virtual Reality.	College students	HMD (stereo)	Practical use	Haywood Community College	Fall 1995 onward
	Updike World	Walkthrough of scene from Updike's *A&P* to identify objects or conditions that do not belong, are important to the scene, or missing.	English 277: Exploring Literature Through Virtual Reality.	College students	Projection screen w/ passive glasses	Practical use	Haywood Community College	Spring 1996 onward
	Nursing World	Walkthrough of "typical" residential house with furnishings. The student is tasked to identify furnishings and other components of the home environment that could be obstacles to patient rehabilitation.	For use in several courses in the Nursing Curriculum.	College students	HMD (stereo)	Practical use	Haywood Community College	Spring 1997 onward
	Milling Machine	Simulation of the actions of milling machine cutting parts from metal stock. The simulation is guided by a Computer-Numerical Control (CNC) student program. The student may change viewpoints during the process and view the final product.	MEC 207: Introduction to CNC Machines.	College students	Projection screen w/ passive glasses	*Practical use*	*Haywood Community College*	*Fall 1997 onward*
Interface Technologies Corporation	Virtual Environment Science Laboratory (VESL)	Representation of the solar system where students can visit any planet, and the sun, manipulating variables such as mass and velocity. Game-like, experiential paradigm that teaches critical concepts. As a user learns about features in the world, he gains virtual tools (e.g., that shrink or expand space, and slow down or speed up time) that permit further explorations. Games also allow the user to conduct experiments where observation of results facilitates learning of linear and orbital mechanics.	AAAS's Benchmarks for Science Literacy, The Physical Setting: The Universe, The Structure of Matter, Energy Transformations, Motion; NRC, National Science Education Standards, Content Standards 9-12: Science as Inquiry, Physical Science, Earth and Space Science.	Grades 9-12, including students with physical disabilities	HMD (stereo)	Subjective usability evaluation	Students, teachers, assistive device specialists, human factors engineers, occupational therapists	1994-1996
						Subjective effectiveness evaluation	Students and teachers from schools in Santa Cruz County, CA	1994-1996
						Effectiveness evaluation	Students from schools in Santa Cruz County, CA	1994-1996
						Practical use	Several schools in CA, 1997	
							Commercially available, 1997	

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
James Cook University, School of Education (NZ)	Room World	Scene of a square room without doors or windows, containing 27 color objects such as dining and lounge furniture.	N/A	Grade 6	Desktop	Evaluation of impact of immersion on recall	Townsville primary schools, Australia	Summer 1995
	Great Pyramid	Depiction of the Great Pyramid, the inside of which is hollow showing various passageways and chambers.	Appreciation of pyramid structure.	Grade 7	Desktop	Subjective effectiveness evaluation	Townsville primary schools, Australia	Summer 1995
	3D Letter World	Colored letters appearing in a giant alphabet ring suspended in the air against a background of blue sky.	Letter recognition.	Grade 2	Desktop	Effectiveness evaluation (unable to be completed)	Townsville primary schools, Australia	Late 1995
Learning Sites, Inc.	Gebel Barkal: Temple B700, Nubia	Walkthrough of recreation of the ancient Nubian temple B700 (ca. 650-640 BCE) and its environs. Objects are linked to text, image, and narrative databases containing interpretive and diactic information, 19th century drawings, and excavation photos.	Understanding of Gebel Barkal site.	Graduate students, archeolo-gists	HMD (stereo)	Practical use	VR Lab, Ministry of Education, Republic of Egypt	Spring 1996
						Exhibition	Museum of Fine Arts, Boston, MA	Spring 1996
						Practical use	Commercially available since 1996	
	Vari House, Greece	Walkthrough of linked virtual worlds depicting an excavated and reconstructed Hellenistic farmhouse (ca. 325-275 BCE) in Attica and its environs. Hyperlinked files contain text and images about the site, and problem-solving tasks for teaching critical thinking, planning, and specific competency objectives.	North Carolina Standard Course of Study Competency Goals and Objectives for World History, Culture, and Geography; Society for American Archaeology guidelines for teaching archaeology in public schools.	Grades 9-12	Desktop	Field testing	10 schools in the U.S. and Canada	Spring 1997 ongoing
						Practical use	Limited prototype available on Web since December 1996	
							Commercially available by fall 1997	
NASA/Lewis Research Center	Virtual Biplane	Biplane with joystick control and functional instruments (airspeed, altimeter, compass, fuel remaining). Participants can look forward to see terrain ahead, look out of the sides of the plane to see terrain below, or back to see terrain travelled over.	Appreciation of flight.	Grades 9-12	HMD (stereo)	Practical	Various	Spring 1997 onward

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
North Carolina State Univ. Comp. Science & Comp. Eng. Depts., Univ. of North Carolina Medical School	Street World	Simple street scene with buildings and a sidewalk, one car and one stop sign.	N/A	Autistic children, ages 6-12	HMD (stereo)	Evaluation of whether VR can benefit autistic children	Chapel Hill and Wake County public schools	Fall 1994
	Object World	Simple worlds including classroom objects and features (such as color).	Object identification.	Autistic children, ages 6-12	HMD (stereo)	Comparative evaluation of VR and conventional teaching methods	Chapel Hill and Wake County public schools	June 1997 ongoing
Oregon State University, School of Education	Science Education World	Travelling in a virtual "pod," students examine plant (the Folanum tuberosum) structure, anatomy, and physiology. Two levels of detail are shown, including mechanisms used to transport fluids from roots to leaves. Speech and textual information are available on request.	Conceptual understanding of nature and experimental method.	High school	HMD (stereo)	Pilot study	Eugene 4-J school district	Spring 1997 ongoing
	Spatial Relations Worlds	Series of 3 worlds: an office-like room where furniture can be moved, a racquetball court where objects can be moved, and a outdoor environment where target objects are to be distinguished between their transformed or mirror model.	Spatial problem solving abilities.	Ages 8-11	HMD (stereo)	Evaluation of impact of immersion	Elementary summer school program in Novato, CA	1992
Sheffield Hallam University (UK)	Greek Villa	Depiction of an ancient Greek domestic residence with 8 rooms, 2 floors, a courtyard, and many objects. Sound effects contribute to the atmosphere, windows and doors open and close, and some animation is used.	National Curriculum Key Stage 2 History Unit, "Ancient Greece."	Ages 8-10	Desktop	Effectiveness evaluation	St. Patrick's Catholic School, Sheffield, UK	Spring 1996
						Effectiveness evaluation	*Firs Hill Junior School, Sheffield, UK*	*TBD*
						Practical use	*Commercially available TBD*	

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
University of Houston, George Mason University, & NASA Johnson Space Center	NewtonWorld	Open corridor activity area where 2 balls of various masses move and rebound, and moveable cameras record events. Signs indicate the presence of absence of gravity and friction, columns and floor markings support judgements of distance and speed, potential energy is portrayed by tactile and visual cues, and velocity through auditory and visual cues. Parameters such as gravity can be changed via a control panel. The world supports guided inquiry into the kinematics and dynamics of 1D motion, with scaffolding to advance the user from basic to advanced activities. A user is tasked to predict forthcoming events, experience them, and explain the experience.	Exploration of Newton's Laws of Motions as well as conservation of both kinetic energy and linear momentum.	Grades 5-10	HMD (stereo)	Formative usability evaluation	High school in Houston, TX	Summer 1994
						Subjective effectiveness evaluation	American Assoc. of Physics Teachers '94 Summer Meeting	Summer 1994
						Evaluation of multisensory interface	Clear Creek, Clear Lake High Schools, Houston, TX	December 1994 - May 1995
						Evaluation of content and lesson structure	Deer Park Elementary School, Rocky Run Intermediate School, VA	Spring 1997 ongoing
						Evaluation of age group, ego vs. exocentric viewpoints, multisensory interface	*Elementary and Junior High Schools in Fairfax, VA*	*Fall 1997*
						Field testing	*TBD*	*1998*
	MaxwellWorld	Boxed area where a user positions a charge configuration and uses a positive test charge, electric potential meter, or electric charge line to query the potential at selected points, and drops test charges into the world. Resultant forces, electric field lines, potentials, equipotential surfaces, and lines of electric flux are displayed. Flux of an electric field through Gaussian surfaces can be visually measured.	Exploration of electrostatics, leading up to the concepts of electric field (force), electric potential (energy), superposition, and Gauss's Law.	Grades 5-10	HMD (stereo)	Formative usability, learnability, effectiveness evaluation	Robinson High School, Fairfax, VA and University of Maryland	Summer 1995
						Comparative effectiveness evaluation	Robinson High School, Fairfax, VA	Spring 1996
						Evaluation of effect of frame of reference	*George Mason University*	*Fall 1997*
						Field testing	*TBD*	*Late 1998*

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
University of Houston, George Mason University, & NASA JSC (continued)	PaulingWorld	Flythrough of a molecular structure represented in various forms. (Being extended to include display of equipotential surfaces and ability to interactively explore effects of atom removal and substitution through direct links to molecular modeling applications.)	Learn about probability density, wave functions, nuclear charge, and atomic orbital shapes for single atoms, bonding of 2 atoms, differences between bonded structures, determinants of bonding angles and length.	High school	HMD (stereo)	*Formative evaluations*	*TBD*	*Mid-1998*
University of Illinois, NCSA, and TRI	Crossing Streets	Set of 3 worlds each showing a different street intersection (one is modeled on an actual street near 2 schools. Each world includes traffic patterns with moving cars. Students are tasked to cross the street safely in a range of situations.	Transportation-related skills.	K-12	CAVE	Evaluation of learning transfer	Various public schools in Urbana and Champaign	Fall 1996 ongoing
University of Ioannina, Dept. of Primary Education (Greece)	virtuaL Approach to the Kernel of Eutrophication (LAKE)	Series of linked virtual worlds demonstrating the process of lake eutrophication. The user can manipulate the system behavior to identify key factors and their relationships. Fifteen predefined starting viewpoints are provided.	Basic concepts in eutrophication.	College (education) students	Desktop	Evaluation of usability and comparison of navigation devices	University of Ioannina	1995-1996
University of Michigan, Dept. of Chemical Engineering	Vicher (I and II)	In each of two Vicher worlds, students are guided by a set of questions and a list of things to see and do to learn about industrial responses to catalyst decay and non-isothermal effects in reactor design. Each Welcome Center provides educational input from books and TVs. Students can visit 6 different reactor rooms, defining operating conditions and "operating" all the	CHE 344: Reaction Engineering and Design.	College students	HMD (stereo)	Formative evaluation (I)	University of Michigan	Early 1995
						Practical	University of Michigan	Spring 1995 onward
						Formative evaluation (II)	University of Michigan	Spring 1997 ongoing

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
University of Michigan, Dept. of Chemical Engineering (continued)	Vicher (I and II) (continued)	equipment to observe effects of, say, changing feed rates on reaction conditions. Three microscopic exploration areas are also available.				Off-site beta testing	University of North Carolina, Michigan Tech, Georgia Tech	July 1996 ongoing
						Publicly available (distributed by CACHE Corporation, Austin, TX)		*Fall 1997*
	Safety World	Students navigate through a pilot plant (for production of polyether polyols from materials such as ethylene oxide) to learn how to perform safety and hazard evaluations. Safety features include a sprinkler system, pressure relief systems, blowout panels, and emergency showers. Plant environs include a hospital and a river providing city drinking water. Objects provide hypertext information and photos of the actual plant. Material safety data sheets are also available.	CHE 486: Chemical Process Simulation and Design I.	College students	HMD (stereo)	Formative evaluation (I)	University of Michigan	Fall 1995
						Practical	University of Michigan	Fall 1995 onward
						Formative evaluation (II)	University of Michigan	Fall 1996 ongoing
						Publicly available (distributed by CACHE Corporation, Austin, TX))		*Fall 1997*
University of Missouri, Dept. of Geography	Map Interpretation World	Flythrough of a central Missouri landscape based on geological survey data. Vertical scale adjusts by factors of 5 and 10 to support understanding of the effects of vertical exaggeration. (Plan to address addition map interpretation issues).	Geography 137: The Language of Maps.	College students	Glasses (passive, shutter)	Practical	University of Missouri	Fall 1996 onward
	3D Map World	GIS-based VE that shows various maps, in layers, of a 3D terrain map that can be used to investigate environmental problems.	Geography 137: The Language of Maps.	College students	Glasses (passive, shutter)	*Practical*	*University of Missouri*	*Spring 1998 onward*

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
University of Nottingham, Dept. Manufacturing Engineering & Operations Management, VIRART Group (UK)	Makaton World	A set of 6 worlds, each of which depicts a "warehouse" of 3D examples of a Makaton symbol. When a user enters the warehouse, an animated sequence is triggered to show the dynamic hand sign for the symbol. The user can view objects from all angles and interact with them to see their function. After a limited number of new symbols have been encountered, the user's ability to correctly identify their meaning is tested in a "reward warehouse."	Teaches Makaton symbols and associated sign language.	Severely learning disabled children	Desktop	Pilot study	Shepherd School, Nottingham, UK	Fall 1992
						Effectiveness and usability evaluation	Shepherd School, Nottingham, UK	Summer 1994
						Practical use	Shepherd School, Nottingham, UK	Summer 1993 onward
							Commercially available from ROMPA, Chesterfield, UK since summer 1995	
	Life Skills Worlds	Several worlds representing a virtual city, house, supermarket, skiing, kitchen, high street, town, and bowling green. Some teach life skills; in the virtual supermarket, for example, the user pushes around a trolley, selects goods, and takes them to the checkout. Others provide experiences; in the city, for example, the user can experience driving around encountering traffic lights, road works, pedestrian crossing, one-ways traffic systems, and other cars.	Supports development of self-directed activity.	Severely learning disabled children	Desktop	Evaluation of skill transfer, promotion of self-directed activity (Virtual Supermarket)	Shepherd School, Nottingham, UK	Early 1996
						Comparative evaluation of effectiveness (Virtual House)	Shepherd School, Nottingham, UK	Fall 1996 ongoing
						Practical use	Shepherd School, Nottingham, UK	Summer 1993 onward
							Commercially available from ROMPA, Chesterfield, UK since summer 1995	
						Evaluation of effectiveness	Shepherd School, Nottingham, UK	Spring 1997 ongoing

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
University of Nottingham, VIRART Group (continued)	AVATAR House	Exploration of a house (kitchen, bathroom, living room) containing recognizable objects that emit sounds when activated. Rooms are designed to focus the user onto certain objects and activities to provide a means of practising skills and to link with real-world activities.	Supports development of concentration skills, improved attention span, self-confidence.	Autistic children	Desktop	Evaluation of effectiveness	Shepherd School, Nottingham, UK	1996 ongoing
University of Portsmouth (UK)	Energy Conservation	The virtual world provides students with a subsection of a city, composed of different types of buildings. Some buildings have associated energy ratings and students must perform energy analyses to provide energy ratings for other buildings. Students can look at energy data to evaluate the cost of improvements under budget/time restrictions.	National Curriculum in Physics, Key Stages 3 and 4.	Ages 13-16	Desktop	*Practical*	*St. Luke's School, Portsmouth, UK*	*Fall 1997*
University of Washington, HITL	Phase World	Presentation of 3D graphs (surfaces) showing relationships among volume, pressure, and temperature when changes in state occur. The user can fly over surface and at interesting points zoom in to observe what happens at the molecular level.	Understanding, at the molecular level, of what happens when matter changes from solid to liquid to gas, and relationships among pressure, temperature, volume.	Grade 11	HMD (stereo)	Comparative effectiveness evaluation	Kennedy High School, Seattle, WA	January 1995 (analysis ongoing)
	Atom World	Open area with sources for subatomic elements, metered scale for changing electron charges, atom assembly area, and notice board identifying atomic element to be constructed. Electron shells are depicted as spheres that change color when an element is completed.	Review of basic atomic and molecular structures.	Grade 11	HMD (stereo)	Evaluation of impact of immersion and interactivity	Garfield High School, Seattle, WA	1994-1995
						VRRV use	VRRV/Nebraska participants	1996-1997

Table 2. Characteristics and Usage of Pre-Developed VR Applications (continued)

Developer	Name of Application	Description	Courses/Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
University of Washington, HITL (continued)	Zengo Sayu	Japanese-style tatami room containing a table, chair, a number of spheres, and a box. Provides a whole language approach to teaching some Japanese nouns, verbs, and prepositions.	Teaching Japanese.	College students	HMD (stereo)	Comparative effectiveness evaluation	University of Washington	January-March 1996
						Practical use	Windows NT version commercially available, 1997 (productized by FirstHand, Inc.)	
	Global Change	Depiction of the Seattle landscape and Puget Sound from space, an aerial view, and a ground level view. Inquiry-based scenario where user assumes role of a alien visiting a world with problems. By setting levels of industry, cars, and forestation, and taking measurements as moving forward or back in time, the user can see the effect of these factors on the environment. Controls consist of wheels to set the level of the factors that impact global change, and a time dial to set the year. A gauge shows current temperature.	Understanding the basic relationships among the causes and effects of global change.	Grades 7-10	HMD (stereo)	Effectiveness evaluation	VRRV Entrée participants	Fall 1996 (analysis ongoing)
						Practical	Available on Internet as part of the Teacher/Pathfinder program	1996 onward
						Proof of concept for multiuser, distributed use	Childrens' Hospital and local school	January 1997 ongoing
	VRRV Hors d'Oeuvre	A selection of commercially available or researcher-developed virtual worlds that demonstrate VR technology and applications.	N/A	Grades 4-12	HMD (stereo)	Evaluation of enjoyment, ease of navigation	Various school in Washington and Nebraska	1994-1997

Most practical classroom applications have been integrated into specific courses or curricula. While some have been developed to meet a teacher's needs for a particular class and are not expected to be used elsewhere, others are intended for widespread use. Different mechanisms are being used to make such applications publicly available. Practical use applications that are already marketed as commercial products are VESL, Gebel Barkal: Temple B700, Vari House, Makaton World, and Life Skills World. Learning Sites, Inc., has taken a useful step in its marketing of Vari House by making a prototype of the application, and sample supporting documents, available for free downloading on its Web site. This marketing step gives potential buyers an opportunity to experience (part of) the Vari House world before deciding whether to purchase a license that entitles them to complete copies of all materials. The University of Michigan is making its Vicher and Safety worlds available at a minimum cost that covers only the price of the materials used and associated shipping costs. Two applications, Greek Villa and Zengo Sayu, that were initially developed as research vehicles also are expected to become commercially available. The three ScienceSpace worlds (NewtonWorld, MaxwellWorld, and PaulingWorld) are also expected to see practical use, although how these worlds will become publicly available is not known at present.

3.1.2 Educational Subjects Supported

Among them, the current set of pre-developed educational VR applications provide support for students from elementary school to graduate school. Discounting those few applications that are intended for use by all age groups, applications are fairly equally split between those designed for elementary and middle school levels, those for high school students, and those for college students (undergraduate and graduate).

Table 4. Educational Subjects

Aeronautics	Virtual Biplane
Animal behaviors	Virtual Gorilla Exhibit
Architectural design	CDS
Ancient Structures	Great Pyramid, Classical Buildings
Ancient Structures/Cultures	Virtual Egypt, Virtual Pompeii, Gebel Barkal: Temple B700, Vari House, Greek Villa
Biology	Cell Biology
Chemistry	PaulingWorld
Chemical Engineering	Vicher (I and II), Safety World
Environmental Science	Global Change, Eutrophication, Energy Conservation
Geography	Map Interpretation World
Industrial Arts	Milling Machine
Language	Makaton World, Zengo Sayu
Letter Recognition	3D Letter World
Literature	O'Conner World, Updike World
Nature, Experiential Method	Science Education World
Object Identification	Object World
Physics	VESL, NewtonWorld, MaxwellWorld, Phase World, Atom World
Real Life Skills	Virtual Bicycle, Crossing Streets, Street World, Life Skills Worlds, AVATAR House
Rehabilitation	Nursing World
Spatial Relations	Special Relationships World

The range of educational subjects covered is quite broad, showing a fairly equal split between the arts and sciences. However, as can be seen in Table 4, there is a predominant subject in each of these fields. For the arts, over one third of the applications address ancient civilizations, looking at either just ancient structures, or also considering cultural concerns. In the case of the sciences, the most popular subject is physics, followed by environmental sciences. The applications designed for science learning show the greatest diversity of virtual worlds and, usually, the most complex worlds. The virtual worlds used in the arts area tend to consist of simple buildings and objects.The science-related applications show the most evidence of explicit pedagogical support.

Table 5. State and Other Learning Objectives

VESL	- AAAS, Benchmarks for Science Literacy, The Physical Setting: The Universe, The Structure of Matter, Energy Transformations, Motion. - NRC, National Science Education Standards, Content Standards 9-12: Science, Inquiry, Physical Science, Earth and Space Science.
Vari House	- North Carolina Standard Course of Study Competency Goals and Objectives for World History, Culture, and Geography. - Society for American Archeology guidelines for teaching archeology in public schools.
Greek Villa	- (UK) National Curriculum Key Stage 2 History Unit, "Ancient Greece."
Energy Conservation	- (UK) National Curriculum in Physics, Key Stages 3 and 4

To support achieving their educational goals with respect to specific subject areas, a few of the applications were developed to meet specific state curriculum objectives or the requirements of certain organizations, as indicated in Table 5.

Reflecting the extent to which a pedagogy is embodied in the virtual world, these applications also differ widely in the extent of teacher support that is provided. Most notable are Vari House, which is accompanied by an 80-page Teacher Guidebook, 25-page Student Workbook, background information sheets, and a special electronic mail list for users; VESL, which is supported by a 3-day teacher workshop with accompanying manuals and curricula material; and Virtual Biplane which, as part of the MAEL program, is supported by pre- and post-visit activities for both teachers and students at the schools visited.

The majority of applications intended for practical classroom use are, of course, accessed in the classroom. The exception is the Classical Buildings application used by the Correspondence School, a distance learning institution in New Zealand. The learning institute is incorporating existing virtual worlds of Greek and Roman buildings into its Classical Studies course by mailing computer discs with these worlds, and the Virtus Player freeware needed to run them, to students. The students can then walkthrough the worlds on their own PCs or Macs to gain information appropriate to specific portions in the course.

Overall, the majority of research has been conducted with students using equipment routinely available in the classroom. Many of the HITL's research efforts, however, have involved the researchers taking special equipment to schools for, usually, short periods of time. Alternatively, the evaluations of the ScienceSpace worlds (that is, NewtonWorld, MaxwellWorld, and Pauling World) are being conducted by bringing students to the equipment at the University of Houston and George Mason University.

3.1.3 Pedagogical Support

Just over a third of the applications rely on minimal interaction and simple walkthroughs of a virtual world to support their educational objectives. These applications are identified in Table 6. This approach can be very effective despite its lack of any specific embedded pedagogy.

For example, the University of Michigan, Department of Chemical Engineering's Safety World allows students to navigate through a recreation of an actual pilot plant for the production of polyether polyols in order to learn about analyzing plant safety. Students can see safety features such as pressure relief systems and emergency showers, and also consider the impact of possible plant failures on the local environment. The walkthrough is supported by links to hypertext information, photographs, and material safety data sheets. As another example, Haywood Community College's Milling Machine allows students to study the effect of the programs they develop for driving a milling machine by walking through a simulation of the procedure while changing viewpoints. In one case, the purpose of the VRRV Hors d'Oeuvre effort was not to teach any particular classroom subject but to provide participants with an awareness of VR technology and its possible applications; here no pedagogy was needed. Some of the applications in this group, such as the Science Education World, are likely to add explicit pedagogical support in the future.

Table 6. No Pedagogical Support

Virtual Egyptian Temple
Virtual Pompeii
Classical Buildings
CDS
O'Conner World
Updike World
Milling Machine
Nursing World
Room World
Great Pyramid
3D Letter World
Gebel Barkal: Temple B700
Science Education World
Spatial Relations Worlds
Safety World
VRRV (Hors d'Oeuvre)

Those applications that explicitly embody some form of pedagogy all support constructivist learning, using an experiential or guided-inquiry paradigm. The particular approach used in each case is identified in Table 7. The Virtual Gorilla Exhibit takes an experiential approach. By allowing participants to assume the role (silverback, adult male and female, juvenile, infant) of different members in a virtual gorilla family and interact with the virtual gorillas, this exhibit teaches about gorilla social hierarchies and behaviors. Another application following an experiential paradigm is the Virtual Bicycle. Here participants use a specially-modified bicycle to cycle round a route where various hazardous conditions occur. The rider must deal with these conditions, which are based on statistical analysis of bicycle accidents, and his performance is guided and critiqued by a virtual mentor. MAEL's Virtual Biplane is intended to provide students with a basic appreciation of flight. This application differs from the others in that it is intended to support additional educational activities. For example, the curricula at different workstations, including an aircraft design workstation, miniature wind tunnel, amateur radio station, remote sensing

Table 7. Type of Pedagogical Support

Virtual Bicycle	Experiential
Cell Biology	Guided-inquiry
Virtual Gorilla Exhibit	Experiential
VESL	Guided-inquiry
Vari House	Guided-inquiry
Virtual Biplane	Experiential
Street World	Experiential
Object World	Experiential
Greek Villa	Learning talk, guided-inquiry
Crossing Streets	Experiential
LAKE	Guided-inquiry
NewtonWorld	Guided-inquiry, scaffolding
MaxwellWorld	Guided-inquiry
Pauling World	Guided-inquiry
Vicher (I and II)	Guided-inquiry
Map Interpretation World	Guided-inquiry
Makaton World	Experiential
Life Skills World	Experiential
AVATAR House	Experiential
Energy Conservation	Guided-Inquiry
Phase World	Guided-inquiry
Atom World	Guided-inquiry
Zengo Sayu	Whole language learning
Global Change	Guided-inquiry

workstation, and flight simulator, are ultimately expected to interconnect to create the experience of preparing for and performing a cross-country flight. The MAEL curricula as a whole are being jointly developed by NASA/Lewis Research Center and Cuyahoga Community College. MAEL will be used to support the Science, Engineering, Math, and Aerospace Academy (SEMAA) K-12 education program developed by these two groups. The Crossing Streets application is based on previous work at the University of Illinois on general-case instruction and behavior self-management models. Here, students are presented with three different types of street intersections to learn to cross the street carefully under a variety of traffic patterns.

The other experiential worlds are specifically intended for use by learning-disabled or autistic students, and are discussed in the following section. By allowing students to experience various activities in a virtual world, these worlds are intended to will help these students learn basic skills that will help in their daily lives.

For the guided-inquiry applications, the pedagogical support is provided in different ways. In several cases, the pedagogy is not embedded into the virtual world but provided by means of associated textual materials. Vari House is one such application. This set of linked virtual worlds provides students with walkthroughs of the archaeological excavation site in Vari, Greece, and a reconstruction based on the building remains that were found. The desktop format allows textual materials to be presented alongside the each virtual world, and these materials provide a demonstration of how archeologists determined, for example, the occupation of the building's occupants. Students are guided in developing their own critical thinking skills by answering questions such as: What factors might tell us about the date of the building? What do you think the circular stones with the central depressions were used for?

For Map Interpretation World, instructors plan to post questions that will guide student use of the world as part of a Web-based course syllabus. As the course progresses, students can return their responses to these questions electronically, including links to the virtual world in their discussions as appropriate.

The Vicher worlds also rely on non-embedded pedagogy, guiding students' learning about reaction engineering and design by means of a one-page list of things to do and see in the virtual worlds and a short list of questions to answer. The example list and set of questions shown in Figure 4 serves to indicate how well this approach can guide student interactions with virtual worlds. Actual development of the Vicher worlds was guided by consideration of Bloom's Taxonomy of Educational Objectives and Felder and Silverman's classification of learning styles [Bell and Fogler, 1995]. Currently, the Vicher worlds target levels 2, 4, and 6 (comprehension, analysis, and evaluation) of Bloom's taxonomy and the application is intended to support "active," "visual," "inductive", and "global" learners. The Vicher worlds are more interactive than those previously discussed. They allow students, for example, to define the operating conditions for several different types of chemical reactors so that they can observe the effects of changes, looking for pertinent relationships.

The MaxwellWorld, LAKE, Global Change, and Phase World applications are similar in the way they support guided-inquiry learning. Each allows students to change world parameters and observe the effects. Using MaxwellWorld as an example, student tasking typically follows the form of the teacher first describing the activity that is to be performed; then the student predicts what is going to happen, completes the activity and observes what actually happens; and finally the student describes what he sees and compares it to what was predicted. Figure 5

<u>List of Things to See and Do in Vicher I</u>

Things to see and do in the Welcome Center: The main thing to do here is to practice using the controls and get comfortable with the experience. Can you crawl under the tables? Ride the escalator? Watch some TV to learn the use of the mouse and get a preview of other rooms. Get some help on something in the room. When you are ready you can walk through any of the doorways to teleport to other rooms. But don't walk though the exit until you are ready to quit the program!

Things to see and do in the Transport Reactor Room: The television (to your right) will explain the equipment and how it works. Use the control panel to turn the equipment transparent. Observe the coking/decoking process. How does this change when you change the flowrates? Watch the cutaway view of the tracer coke and decoke. "Activate" any pellet for a closer view.

Things to see and do in the Time-Temperature Room: Watch TV. Turn on the reactor power to start an experiment. The clock and calendar mark time. Observe how conversion declines with declining activity at constant temperature. How long until shutdown? Activate the "HEAT FX" button to control temperature for constant conversion. Then push power and note the time until shutdown. Try some different target conversions to observe the tradeoffs.

Things to see and do in the Microscopic Areas: Outside the pellet, observe external diffusion. Fly inside to observe reactions taking place inside the pores. The red hexane modules are the reactants - follow one until it reacts. The orange intermediates will also react. If you have difficulties, watch the targets - they are rigged for easy observation. (Note: The targets are NOT the only active sites - they are just easier to watch.) You can fly through the targets for a closer look. Then activate or fly through the pictures to get back out.

<u>Study Questions for Vicher I</u>

1. In the transport reactor room, how do the flowrates of hexane and oxygen affect the coking/decoking process? Can you identify trade-offs of high versus low flowrates?

2. In the time-temperature room, flowrates are constant and conversion is controlled by temperature. Does the catalyst activity decline faster or slower when higher (desired) conversions are chosen? Why? If the temperature is controlled to yield a constant conversion, how does this affect catalyst degradation rates? State at least two trade-offs between reactor performance and shutdown frequency.

3. Inside the catalyst pore, does a reaction take place every time a reactant hits the pore walls? Why or why not? Describe the steps involved when a reaction does take place.

Figure 4. Example Vicher List of Things to See and Do, and Study Questions

provides an example scenario using this approach. NewtonWorld is also similar to these applications: it allows students to change physical laws, such as the coefficient of friction, and observe the effects on a pair of colliding balls in order to learn about the kinematics and dynamics of one-dimensional motion. NewtonWorld, however, provides additional pedagogical support by introducing scaffolding that advances students from basic to advanced activities. PaulingWorld currently is undergoing redesign but is expected to follow this overall approach.

These questions were posed as part of a lesson that teaches about the concept of superposition, that is, that each of the charges in the space influences the strength and direction of the electric field (force) at every point in the space.

The student is looking at a dipole, and has just learned about superposition. Now he is asked to use that concept to predict what will happen at a specific point in the field, and the field as a whole, when he deletes a source charge:

Question 7. **Predict.** Now let's talk about that same trace. Use your finger to show what will happen to that trace when you remove the positive charges. Explain why. What will the field be like in general?

Question 8. **Observe and Compare.** Let's test your hypothesis. Point to the positive charge and double click to delete it. Is this what you predicted? Based on what you just observed, describe specifically what the force meter on a test charge trace reflects in relation to a set of charges.

Figure 5. Examples of Student Questions Used with MaxwellWorld

As with the Vicher worlds, the developers of the ScienceSpace worlds and LAKE, and the HITL researchers have provided information on the pedagogical underpinnings of their applications. The ScienceSpace researchers stress four concerns [Dede et al., 1997b]:

- Students must focus on or be engaged in an experience in order for learning to occur,
- Meaningful representations are necessary to communicate information,
- Multiple mappings of information can enhance learning, and
- Learning-by-doing and reflective inquiry can both induce learning.

In particular, to support mastery of complex scientific concepts, the ScienceSpace worlds are designed to provide learners with experiential metaphors and analogies that aid in understanding abstractions that are remote or contradictory to everyday experience. The developers of the virtuaL Approach to the Kernel of Eutrophication (LAKE) base their world design on general aspects of sensory ergonomics. The LAKE application consists of a series of linked worlds that students can explore to experience successive stages in the development of plant nutrient materials and organisms in lakes.

At the HITL, the researchers believe that immersion is the key issue and that the psychological processes that become active in immersive VR are very similar to those that operate when people construct knowledge through interaction with objects and events in the real world [Winn 1993]. Their applications, therefore, are designed to embody psychological theories pertaining to first-person experiences, non-symbolic interactions, and learning by constructing knowledge.

In a setting of the solar system, VESL also allows students to manipulate variables such as mass, velocity, and time with the objective of learning about linear and orbital mechanics. VESL differs from the previous set of applications, however, in providing a virtual helper that assists the students with exploring the virtual solar system. Context-sensitive help provides additional support, addressing such issues as how to operate the controls, what to do next, and how to interpret the results of experiments from a physicist's point of view.

Atom World and Cell Biology differ from the preceding applications in that participants learn by constructing objects. In Atom World, students review basic atomic and molecular structures by constructing specified structures. These structures are built by selecting items from different sources of subatomic elements and changing electron charges as necessary. Cell Biology uses a game-like approach in guiding participants to learn basic principles of human cell biology. A participant is provided with bowls of different types of organelles that must be combined to form the different types of cell that a sick child needs. Energy Conservation takes a different approach to knowledge construction by allowing students to investigate how the energy saving properties of various building materials impact home energy costs. Students gain practical insights in how to plan for energy-related home improvements by learning how to balance the cost of particular improvements with expected savings over time under various budgetary and time constraints.

Guided-inquiry is supported in the Greek Villa application by asking students to take on the role of time-travellers and to see aspects of the Greek Villa as evidence from which deductions about the Greeks can be made. Additionally, this work is investigating the use of "exploratory talk" in virtual worlds. The concept behind exploratory talk is that a certain type of student-student discourse can contribute to learning more than other patterns of interaction [Grove 1995]. Consequently, this work has attempted to foster students' exploratory talk and is considering whether, and the extent to which, students engagement in this type of discourse can be used as a measure of VR technology's educational value.

Finally, Zengo Sayu adopts a whole language approach for second language learning or, more specifically, a combination of Asher's Total Physical Response (TPR) strategy and Terrell's Natural Approach [Rose and Billinghurst, 1996]. As Rose reports, TPR is a direct assimilation method where the meaning of the target language is conveyed through physical demonstration and does not use any form of translation into the first language. The Natural Approach is a modification of Asher's strategy that supports the concept of a "silent period" for language absorption, incremental knowledge acquisition, concrete associations development, and the use of speech technique to draw attention to critical aspects of the target language. Zengo Sayu supports this combined approach by the use of speech and gesture recognition and digitized speech output in the context of a Japanese-style room where objects can be manipulated.

3.1.4 Support for Students with Special Needs

Table 8. Special Needs Applications

Support for Learning Disabilities
Makaton World
Life Skills Worlds
3D Letter World
Support for Autistic Students
Street World
Object World
AVATAR House
Support for Physical Disabilities
VESL
Science Education World

A few groups have been looking at the potential of VR technology to support students with learning disabilities. The applications that have been developed in this area are identified in Table 8. The leader in this area is the University of Nottingham, Virtual Reality Applications Research Team (VIRART) Group, which has worked in collaboration with the University of Nottingham Medical School, Department of Learning Disabilities. Here, as part of their Learning in Virtual Reality (LIVE) program, researchers have been working closely with staff from a local school for the learning disabled. With the overall goal of developing a methodology for the use of VR technology in special needs teaching, they have proposed a five-step approach that, as stated by Brown et al. [1995], seeks to:

- Embed the development of virtual learning environments in contemporary educational theory,
- Empower users and their care-givers to participate successfully in shaping and defining the educational and rehabilitative applications developed,
- Design and execute a continual program of testing and use these results to refine the virtual learning environments,
- Consider the ethical issues surrounding the involvement of people with disabilities in research and development, and
- Develop a curriculum for use of these environments in special classrooms today.

The VIRART team has already used this approach in developing a number of VR applications for severely learning-disabled students. Makaton World supports learning the Makaton Symbol Vocabulary, a sign language used in the United Kingdom by people with learning disabilities. The application consists of a number of separate virtual worlds, each designed to teach a particular Makaton symbol and associated hand sign. Currently, 50 Makaton symbols are supported, drawn from the first four levels of the Makaton vocabulary. The researchers hope to continue adding new symbols until the whole 350 symbol vocabulary is included. Another series of virtual worlds, the Life Skills Worlds, provides students with an opportunity to learn practical skills (e.g., shopping in a supermarket) or to experience events that would otherwise be inaccessible to them (e.g., driving a car). Life Skills World is currently being extended to include cafe, post office, recreation center, bank, and health center virtual worlds.

Researchers at James Cook University, School of Education, developed a simple world consisting of a ring of alphabetic characters suspended in empty space. The purpose of this 3D Letter World was to determine whether exposure to the virtual world would help young children who had exceptional difficulty in letter recognition. Unfortunately, because of the difficulties the children experience in mastering basic navigation skills, this effort could not be completed [Ainge 1996c]. The researchers attribute the students' difficulties to the lack of adequate hand-eye coordination and spatial awareness. This conclusion suggests that further work is needed to determine the necessary basic skills for exploration of virtual worlds and to assess whether special preparatory training could assist learning disabled students in gaining such skills.

This VIRART researchers are also working on providing support for autistic students. In this case, the AVATAR House application allows a student to explore a virtual house where rooms are designed to focus attention on recognizable objects and activities so that the students can learn practical skills. Researchers at North Carolina State University, working with the Treatment and Education of Autistic and Other Communications Handicapped Children (TEACHC) program at the University of North Carolina Medical School, have also focused on the use of VR to help autistic children. In their first effort, these researchers used Street World to investigate the usability of the technology for this type of user. Based on the success of this evaluation, the researchers are redesigning the VR application to teach identification of basic classroom objects. The new application is called Object World.

Two groups have been working to develop educational VR systems for students with physical disabilities. Following an analysis of the special needs of persons with spinal cord injuries, Interface Technology Corporation developed VESL to provide a virtual physics laboratory that could be used by students with such disabilities, as well as non-disabled students [Nemire 1994]. After performing a study looking at the usability of spatial tracking technology for students with cerebral palsy [Nemire 1995a] and developing special prediction software that would help these students to select targets in a virtual world, Interface Technology Corporation redesigned VESL to additionally support this class of students. Both these design and development efforts included usability evaluations that considered feedback from not only students and teachers, but also assistive device specialists, occupational therapists, and human factors engineers.

The Oregon Research Institute also has taken care to ensure that its Science Education World accommodates the needs of many physically challenged students. One of the mechanisms they employ is a touchscreen. Future versions of the application are expected to include speech recognition so that students can take notes during their investigations.

3.1.5 Hardware and Software Issues

For each developer of educational VR applications, Table 9 summarizes key aspects of the hardware used. The type of hardware platform and peripherals required by an application can have a significant impact on its development and operational costs. Though the high graphics processing capabilities of a powerful Silicon Graphics, Inc. (SGI) machine are desirable for creating highly-detailed worlds with fast frame rates, the high costs of such machines can make them impractical vehicles for elementary, middle school, high school and, in some cases, college education. Recently, SGI, Hewlett-Packard (HP), and Intergraph have all introduced new lines of graphics workstations that provide good graphics performance at substantially lower costs. At the other end of the spectrum, Pentium PCs and the development of powerful graphic accelerators are increasing the power of low-end machines. Consequently, while high-end graphic workhorses have been used as platforms for some of those applications developed as research tools, and as an initial development and evaluation platform for other applications, they are becoming less widely used. The consortium developing ScienceSpace, for example, is porting its applications to PCs, and the University of Washington HITL is considering a move to HP workstations. On the other hand, the University of Michigan, Department of Chemical Engineering, is porting in the reverse direction, from PCs to SGI mainframes to get the processing power needed for its complex Vicher and Safety worlds. The range of SGI machines in use includes the Onyx, Indigo, Crimson/Reality Engine, and Maximum Impact platforms.

The most popular platform for educational VR applications is a PC. The majority of developers are using Pentium PCs with graphic accelerators, although ERG Engineering, Inc. and the Correspondence School have both used 386- or 486-level PCs. Other types of hardware platforms, such as the HP J210 PA-RISC, Intergraph GLZ5, and Division PV 100 workstations, have seen only limited use.

The choice of visual display represents another important decision, one that affects both cost and the degree of immersion experienced by participants. Usually, the ideal situation is full immersive viewing of a computer-generated virtual world, and with current technology this calls for an HMD or CAVE display. HMDs are devices where two miniature display screens (one for each eye) are positioned in front of the user's eyes and viewing through optical lenses that serve to magnify the images. The user's sight is restricted to what can be viewed on the virtual scene projected by the optical system and, hence, the user is visually immersed in the virtual world that is presented. Stereoscopic viewing is achieved by presenting slightly different images on the display screens. A tracking device is usually attached to the HMD so that the virtual scene is updated appropriately as the user turns his head. A CAVE display takes a very different approach. Here the user can move freely within a small "room" constructed of up to six rear projection screens and some type of special glasses are used to provide stereoscopic viewing of the virtual world in which the user is visually immersed. The majority of developers are using relative inexpensive HMDs to provide stereoscopic viewing. While the

Table 9. Hardware Support for Pre-Developed Applications

Developer	Platform						Display						Special I/O				
	SGI	Division Workstation	PC	Macintosh	Intergraph Workstation	HP Workstation	Monitor	Monitor w/ Glasses	HMD	Projection Screen	CAVE w/ Glasses	CyberScope	Speech I/O	Haptic	Spatialized Sound	Hand Device	Motion Platform
Carnegie Mellon University, SIMLAB	✓		✓				✓	✓	✓						✓	✓	✓
Correspondence School			✓	✓			✓										
ERG Engineering, Inc.			✓						✓				✓[a]		✓	✓	
Georgia Institute of Technology, GVU Center	✓					✓			✓							✓	
Haywood Community College		✓	✓				✓		✓	✓						✓	
Interface Technologies Corporation			✓						✓				✓		✓	✓	
James Cook University			✓				✓										
Learning Sites, Inc.	✓		✓		✓		✓		✓								
NASA/Lewis Research Center	✓								✓							✓	
North Carolina State University			✓						✓								
Oregon Research Institute			✓						✓								
Oregon State University			✓						✓							✓	
Sheffield Hallam University			✓				✓										
University of Houston, George Mason University, & NASA JSC	✓								✓				✓[a]	✓	✓	✓	
University of Illinois, NCSA	✓										✓					✓	
University of Ioannina			✓				✓									✓	
University of Michigan	✓		✓				✓	✓	✓			✓				✓	
University of Missouri	✓							✓		✓							✓
Univ. of Nottingham, VIRART Group				✓			✓										✓
University of Portsmouth			✓				✓										
University of Washington, HITL	✓	✓							✓				✓			✓	

a. Digitized speech output only

capabilities of different HMDs vary considerably, current low-cost products (less than $1,000) typically deliver a resolution of around 300 x 400 pixels, and a horizontal field of view of around 30°. Some developers have chosen to use HMDs but provide only monoscopic viewing, thus reducing some of the need for heavy graphics processing.

There are other factors that can influence display choice. If, for example, it is desirable for several students to watch the interaction of one of their colleagues with an application, then the most economical option may be to use a projection screen and provide inexpensive light polarizing glasses so that the audience can watch a 3D display of what the immersed student sees using an HMD. This type of combination viewing is used by students at Haywood Community College. A more expensive alternative, used by the NCSA for Crossing Streets, is to provide for simultaneous immersion of several participants in a CAVE.

In some cases, an application is designed to work with alternative display devices. The widest selection is supported by the University of Michigan's Vicher and Safety World applications. Here, the Visual I/O HMD, Crystal Eyes shutter glasses, and Simsalabim's CyberScope are all supported. (The CyberScope is an optical hood that attaches to a monitor to provide a stereoscopic display.)

Overall, two-thirds of the developers (nearly three-quarters of the applications) provide immersive viewing. For non-immersive, stereoscopic viewing, the use of shutter glasses with a monitor seems to be preferred to a projection screen with passive glasses. Less than one third of the developers rely entirely on the use of a standard desktop monitor for world viewing.

As shown in Table 9, other special input/output devices are being used in addition to the display devices. Often, it is the same small group of developers who provide these types of support. The HITL's Zengo Sayu and Interface Technology Corporation's VESL both use speech recognition and digital speech output, and digitized speech output is also provided in ERG Engineering Inc.'s Cell Biology world and the PaulingWorld from the ScienceSpace series of worlds. All but the first of these developers have also used spatialized sound in some of their applications. The SIMLAB at Carnegie Mellon University also uses spatialized sound. Haptic feedback has been employed in NewtonWorld and MaxwellWorld, in evaluating the impact of multi-sensory feedback on learning effectiveness. The haptic feedback was provided by two different haptic vests, both of which operate by converting sound waves to vibrations.

While some immersive and desktop applications still rely on a traditional mouse as the primary input device, special devices such as joysticks, wands, and six degrees-of-freedom mice are being used with some immersive applications. The most common of these special devices is a joystick. In particular, data gloves are not widely used, largely because of problems in resolution for interpreting gestures. The Street World and Object World designed for use by autistic children use no hand-based input; instead, participants navigate through these worlds via head tracking on the HMDs and walking in a small area. As previously noted, Interface Technology Corporation and the Oregon Research Institute also make special accommodations for physically disabled students: VESL includes a head wand and a spatial tracking device that attaches to the user's hand, and Science Education World uses a touchscreen instead of a mouse.

The Virtual Bicycle and Map Interpretation World provide the first examples of the use of motion platforms in educational VR applications. The Virtual Bicycle uses a specially modified

Table 10. VR Development Software for Pre-Developed Applications

Developer	DVise	Superscape VRT	WorldToolKit	Virtus WalkThrough/Pro	VRDS	BRender	VRML	Custom	Other
Carnegie Mellon University, SIMLAB			✓						
Correspondence School				✓	✓				
ERG Engineering, Inc.			✓						
Georgia Institute of Technology, GVU Center								✓	
Haywood Community College	✓	✓							
Interface Technologies Corporation									✓
James Cook University				✓	✓				
Learning Sites, Inc.			✓				✓		
NASA/Lewis Research Center									
North Carolina State University	✓								✓
Oregon Research Institute						✓			
Oregon State University									✓
Sheffield Hallam University		✓							
Univ. of Houston, George Mason Univ., & NASA JSC								✓	
University of Illinois, NCSA									✓
University of Ioannina		✓							
University of Michigan			✓						
University of Missouri									✓
University of Nottingham, VIRART Group		✓							
University of Portsmouth									
University of Washington, HITL	✓								

bicycle that is mounted on a motion platform to represent the different types of surface that the participant must traverse. For the Map Interpretation World, researchers are considering the use of a motion platform to provide a sense of following geographical contour lines.

Developers' use of particular VR development packages is shown in Table 10. These development systems vary greatly in the tools they provide. The most extensive being Sense8's WorldToolKit, a package that is available for platforms ranging from SGI machines to PCs. Packages such as Superscape's VRT, Virtus' Virtus Walkthrough, and VREAM's Virtual Reality Development System (VRDS) are less sophisticated and used primarily on PC platforms. REND 386 and BRender are early packages that are available as freeware on the

Internet. DVise is the development package that comes with Division's VR workstations. Some developers have chosen to create their own development packages or use available modeling tools. In one case, at the University of Missouri, Department of Geography, a virtual world was constructed using the Multigen database tool and Perfly for the creation of the walkthrough. Other VR software development systems or 3D graphics packages in use include Alice, Renderware, CyberSpace, Quicktime VR, Design it3D, 3D Design Center, Alias Modeling Software, AutoCAD, Modelgen, NCad, Ogre, and Hyperstudio. A simulation software development package called VEGA, from Paradigm Simulations, Inc. has also been used. As can be seen in the table, there are no strong favorites in this area.

One reason why such as wide range of development tools is being used is that no single tool currently supports the range of functionality needed in the development of diverse virtual worlds. Until recently, the incompatibility between these tools has sometimes presented problems for application developers. The continuing development of VRML may, in time, resolve such difficulties. VRML is not a development package that provides developers with a range of tools, but a programming language for the development of virtual worlds that can be viewed using various Web browsers. The main benefit of VRML is that of standardization of virtual world data over the Web. Some development packages (such as VRT, Sense8's WorldToolKit and WorldUp, and VREAM's forthcoming VRCreator) already provide VRML compatibility. The most recent version of VRML, VRML 2.0, still has many limitations, such as a lack of specifying how objects can interact with a multiuser technology. Even so, VRML 2.0 is in the process of becoming an International Organization for Standardization/ International Electrotechnical Committee standard (ISO/IEC 14772), and VRML browsers are expected to become widely available on the Web in the near future.

While only one of the developers (Learning Sites, Inc.) of educational VR applications discussed here is currently using VRML, in January 1997 SGI posted information about the top ten VRML educational worlds (reportedly judged by leading figures in the VRML community) on their Web site. Vari House was selected as one of these award-winning educational applications. The other nine applications are not discussed in this paper because they are essentially VRML demonstration worlds not intended for immediate practical educational research or use. More evidence of the interest in VRML for educational applications is provided by Educational Service Unit #3 of Nebraska (see Section 2). Here, Service Unit staff is currently searching for teachers who are willing to use VRML on the Internet to support a collaborative project.

3.1.6 Extending Beyond Education

Several of the predeveloped VR applications also can be used for non-educational purposes. For example, in their role as exhibition pieces, Cell Biology and Virtual Gorilla Exhibit serve to both entertain and educate. In addition, some of the applications are intended for use by both students and professionals engaged in specific work-related activities. The Conceptual Design Space (CDS) was one such application, providing architects with tools to aid their visualization of architectural spaces. Gebel Barkal: Temple B700 is intended to support archeologists through the provision of links to nested datasets that include relevant archaeological data.

The work of Learning Sites, Inc., in general, deserves special mention for its breadth of vision. The goal of this group is to create a globally integrated and interactive system of linked virtual worlds that can be used for teaching, research, archaeological fieldwork, museum exhibitions, and even tourism. Accordingly, the existing worlds are all based on detailed archeological evidence and provide links to resources such as excavation notes, site drawings, and related historical, geographical, and cultural material. The set of Learning Sites worlds is expected to grow, and some of the existing worlds will be expanded. Gebel Barkal: Temple B700, for example, will continue to expand as more temples are added. To this end, Learning Sites, Inc. is currently in discussion with several archeologists about publishing their excavation results using interactive VRML worlds.

3.2 Student Development of Virtual Worlds

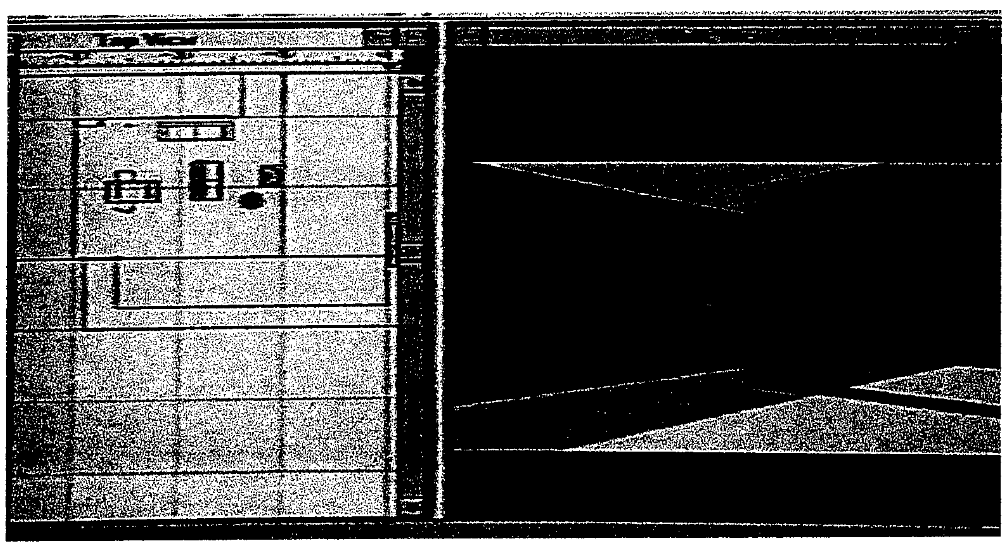
As before, in an effort to start by trying to give some idea of the types of virtual worlds that have been developed by students in the course of learning about particular topics, the Figure 6 and Figure 7 provide descriptive overviews of two of these worlds. A summary of the major characteristics and usage of the efforts considered is given in Table 11. Some of the topics of discussion in the previous section, such as embedded pedagogy and commercial availability, are not applicable for student development of virtual worlds. Consequently, the structure of this section differs slightly from the last, dropping some topics of discussion while adding those more pertinent to student world building.

Before continuing, it should be noted that the work of West Denton High School, Newcastle, England, is not included in the following discussions because of a lack of information. This work was conducted in the early 1990s, but the teachers involved with the work have left the school, which is no longer using VR technology. This work deserves some mention, however, because it was Europe's first school-based VR project. One of the ways in which VR technology was used was to support learning about workplace safety by having students design and build virtual worlds of factories, keeping health and safety rules in mind. Then, using a trackball, they could explore the virtual world, driving virtual lathes and forklift trucks. Some of the VR work was submitted in partial fulfillment of the UK A-Level examination in computing and the Business Technician Education Council (BTEC) diploma in computer studies. It is unfortunate that the overall findings of this work have not been disseminated.

Background on the Icebound Project: Don and Margie MacIntyre wintered over at Cape Denison in Antarctica in 1995. They lived in a 6' x 8' room, which they called the Gadget Hut, that they had designed and tested. Don and Margie communicated with thousands of students across New Zealand, sharing their day-to-day trials and tribulations. (For example, at one time, Don and Margie almost died of carbon monoxide poisoning when a vent hole froze over.) Their way of life became a catalyst for many studies of Antarctica. A class of students at Evans Bay Elementary School, Wellington, NZ, participated in the project, exchanging faxes and email with the MacIntyres and joining in an audio conference.

Work at Evans Bay Elementary School: In an effort to teach communication and critical thinking skills, students were assigned many research activities that required use of VCRs, electronic bulletin boards, electronic mail, CD, and VR technology.

VR Activity: Four students were tasked to design a permanent Antarctica base large enough for two people. The educational objective was to learn and apply critical thinking skills in using knowledge gained from research. The design had to show evidence that all important aspects had been considered. For example, because of a lack of water for fire fighting, the base was divided into separate sections with long connecting tunnels that were collapsible to prevent any fires from spreading. The students also included a refrigerator that would be used to keep things warm, instead of cold.



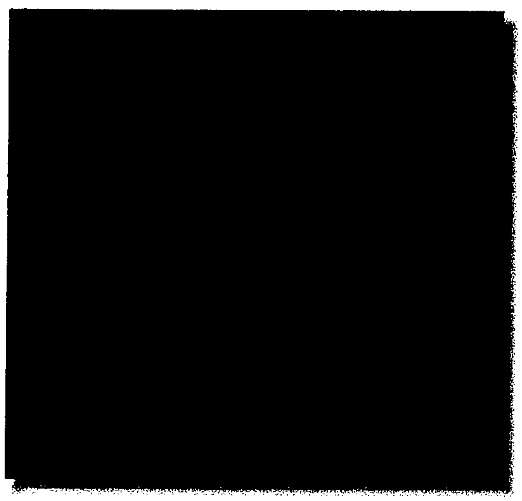
Researcher's Comments: "The students did use critical thinking and applied research - but of course they could have done this using paper - or have made a [physical] model. What the VR software did was allow their ideas to be changed rapidly, explored and developed quickly - redesigning was a breeze. They could conceptualize as a group - taking turns at driving the mouse on the PC. It also allowed presentation of a 3D walk-through so that ideas could be recorded as a 'walkthrough movie' in software. Ideas were seen by the whole group - in 3D. Overall, they used the software very successfully to collaboratively conceptualize, test and present their ideas" [Carey 1997].

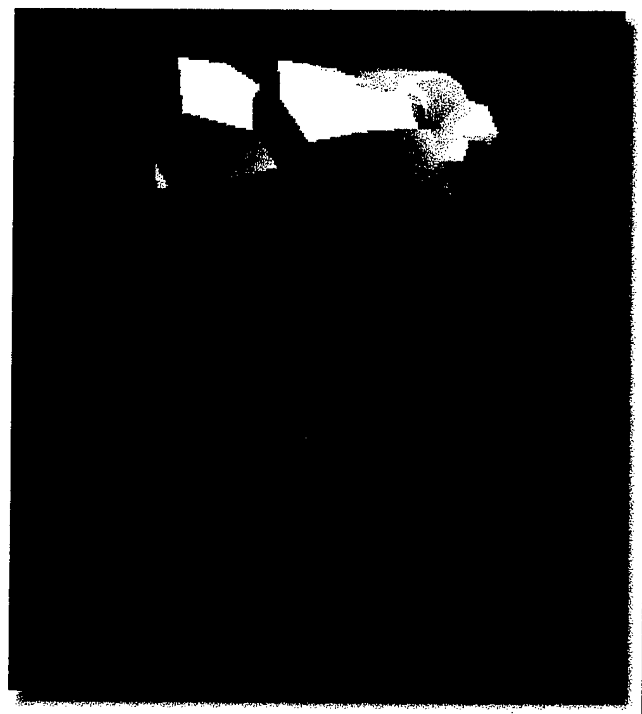
Figure 6. Unit on Antarctica

Project Goal: To test the hypothesis that learning about a wetland cycle using constructivist principles paired with the use of VR technology would yield greater comprehension of subject matter than learning about a wetlands cycle though traditional means.

Pedagogies Compared:

- Constructivist. Two 1.5-hour sessions were spent by students working individually, or with partners, studying general wetlands ecology information and information on an assigned cycle. They selected materials from a library guide, the Internet, CD-ROMs, and video-disks to develop their own understanding of the underlying concepts. No direct instruction was provided. Groups of students then spent two more sessions planning a virtual world for the assigned cycle and creating objects and behaviors for the world. The plans and world components were integrated into a virtual world by HITL researchers. Students experienced the world for their assigned cycle and a world developed by other students for another cycle.
- Traditional. For the first session, students were guided by a teacher in reading appropriate sections of a textbook. Handouts with page numbers tied to the assigned cycle, a keyword list, and a set of study questions to be answered in discussion periods were provided. In the remaining three sessions, students completed flowcharts and worksheets, with specific pages numbers relating to the text. Then some of the students experienced the virtual world for the cycle studied.
- No instruction. Students were given instruction on a unrelated subject.





Developed Worlds:

- Carbon Cycle. Demonstrated CO_2 formation, O_2 formation, and decomposition. Objects included plants that used CO_2 and produced O_2, and animals that consumed O_2 and produced CO_2. Carbon was released into the cycle through the decomposition of flesh or feces.
- Energy Cycle. Demonstrated the food chain and how energy transfers from one organism to another, including decomposition and its contribution to plant growth and regeneration. Objects included blue-green algae, fish, dragon flies, birds, and a duck, turtle, fox, and alligator.
- Nitrogen Cycle. Demonstrated nitrogen fixing, movement of nitrogen through the food chain, denitrofication, decomposition (release of fixed and free nitrogen into the air and soil). Objects included free nitrogen, a lightening storm, rain transferring fixed nitrogen into the ground for absorption by plants, nitrogen fixing bacteria, plants with fixed nitrogen, denitrofying bacteria, and a duck, fox, dead ducks, and feces.
- Water Cycle. Demonstrated cloud formation (condensation), rainfall (precipitation), groundwater accumulation, and water vapor (evaporation). Objects included energy from the sun, water vapor, clouds, rainfall, and a lake representing groundwater accumulation.

Figure 7. Wetlands Ecology

Table 11. Characteristics and Usage of Student Development of Virtual Worlds

Organization	Class/Course	Tasking	Learning Objectives Supported	Intended Audience	Display	Usage	Students' Organization	Date of Use
East Carolina State University	EDTC 6242	Develop a VR application that meets specific curriculum objectives, supporting instructional materials, and demonstration scenario. Conduct empirical evaluation of the application's educational effectiveness.	Build skills in applying VR technology to education.	College students	Desktop, HMD (stereo), glasses	Practical (as independent study course)	East Carolina State University	Spring 1996 onward
Evans Bay Intermediate School	Class work on communications technologies, unit on Antarctica	Using information learned through communicating with a couple wintering in Antarctica in a hut, cooperatively design a permanent Antarctica habitat.	Develop critical thinking skills.	Ages 10-13	Desktop	Practical	Evans Bay Elementary School	Late 1995
	Class work on communications technologies, unit on sports	Following local debate on the advisability of building a new sports stadium, develop stadium designs and walkthroughs of these designs.	Support development of 3D thinking skills and problem solving design issues within set parameters.	Ages 10-13	Desktop	Practical	Evans Bay Elementary School	Mid-1995
	Language program	Work cooperatively to create worlds and stories that develop within them. Video, audio, or text at hot spots carry the narrative.	Develop oral language part of English curriculum: story telling, group discussion, group problem solving; and from the visual language part: present ideas in a visual way.	Ages 10-13	Desktop	Practical	Evans Bay Elementary School	Mid-1996 onward
	Virtual Museum	Working in pairs, decide on a research topic, make a mind map of their existing knowledge, list research questions and conduct research. Present the result as a series of related museum displays, using supporting graphics, text, movies, and sound.	Develop skills in organizing research results.	Ages 10-13	Desktop	Practical (looked at comparative educational effectiveness)	Evans Bay Elementary School	Mid-late 1996
	Virtual Stage	Working to scale, design stage sets for witches' scene in Macbeth using standard sizes of large wooden cubes, and avatars to represent actors' positions.	Develop mathematical concepts of scale and skills in group design.	Ages 10-13	Desktop	Practical	Evans Bay Elementary School	Mid-1996

Table 11. Characteristics and Usage of Student Development of Virtual Worlds (continued)

Organization	Class/Course	Tasking	Learning Objectives Supported	Intended Audience	Display	Usage	Students' Organization	Date of Use
Evans Bay Intermediate School (continued)	Virtual Cemetery	Working in groups, based on research about (in)famous people in history, build a cemetery that shows a classification of the people, with mausoleums with epitaphs and movies of student oral presentations about the people.	Develop skills in organizing research results.	Ages 10-13	Desktop	Practical	Evans Bay Elementary School	Late 1996
Haywood Community College	English 277: Exploring Literature Through Virtual Reality	Use VR as a literary analysis tool by developing a series of simple worlds that portray scenes from a reading assignment, and a final world that addresses teacher-supplied questions.	To explore how writers use words, images, symbols, and settings to create a mood, develop characters, or dramatize a story theme.	College students	HMD (stereo), projection screen w/ passive glasses	Practical	Haywood Community College	Spring 1996 onward
H.B. Sugg Elementary School	Virtual Pyramid	Working in groups, build a pyramid, move objects in and out, and view the pyramid from different perspectives.	North Carolina Standard Course of Study Objectives 2.1, 2.2, and 2.3.	Grade 5	Desktop	Evaluation of effectiveness	H.B. Sugg Elementary School	Early 1995
James Cook University, School of Education	Mathematics (3D Shapes)	Working in pairs, create a world and populate it with a specified set of 3D shapes, then interact with it.	To develop skills in visualizing and recognizing 3D shapes form various viewpoints.	Grades 6-7	Desktop	Comparative educational effectiveness evaluation	Townsville primary schools, Australia	May-July 1995
	Historical Home	Working as a group, select a period in history, research domestic life, and built a virtual home that illustrates this life style.	To develop skills in researching and understanding of domestic life in historical cultures.	Grade 7	Desktop	*Comparative educational effectiveness evaluation*	*Townsville primary schools, Australia*	*Late 1997*
Kelly Walsh High School	Math Worlds	Develop worlds that support learning in pre-calculus and geometry including, for example, worlds for plotting coordinates in 3-D and functions revolving around the *x*-axis.	Various mathematical topics in pre-calculus and geometry.	Grades 10-12	HMD (stereo), shutter glasses	Practical use	Kelly Walsh High School, Casper, WY	Fall 1993 onward

Table 11. Characteristics and Usage of Student Development of Virtual Worlds (continued)

Organization	Class/Course	Tasking	Learning Objectives Supported	Intended Audience	Display	Usage	Students' Organization	Date of Use
Kelly Walsh High School (continued)	Computer Programming class	Research an educational area where VR seems applicable (not math or programming topics and something that cannot be done by hand) and create an educational virtual world for the selected topic.	Various topics.	Grades 10-12	HMD (stereo), glasses	Practical	Kelly Walsh High School, Casper, WY	Fall 1993 onward
						Comparative effectiveness for correcting science misconceptions	2 high and 3 elementary schools in Natrona School District #1, WY	1993 - 1994
Slaton Independent School District	Class on Atomic and Molecular Structure	Working in groups, research a particular atomic or molecular model and build a virtual world that showing understanding of the atom structures involved (numbers of protons and neutrons in the nucleus, and electron spacing).	To develop an understanding of an atom and its parts.	Ages 15-16	Shutter glasses, projection screen	Practical	Slaton High School, Slaton, TX	January 1996 onward
	Class on Energy Conservation	Working in groups, select a (U.S. or world) area you would like to live in, and research climatic data and other information about heating, cooling, house structures, etc. Then prepare house blueprints and create virtual worlds that provide 3D renderings of the blueprints.	To provide an understanding of costs involved in home maintenance and learn to develop energy conservation techniques to reduce the cost of living.	Ages 15-16	Shutter glasses, projection screen	Practical	Slaton High School, Slaton, TX	January 1996 onward
University of Washington, HITL	Pacific Science Centre, Summer Camp '91	Working in teams, decide on a world to build, plan the work, create 3D objects and define interactions (HITL staff use these to actually build the virtual worlds), then view these world.	Develop an understanding of VR technology.	Ages 10-15	HMD	Determine if students could work creatively and enjoyably with VR	Pacific Science Center, Creative Technology Camp	Summer 1991
	Pacific Science Centre, Summer Camp '92	Working in teams, take an abstract concept and incorporate it into a virtual world with an emotional theme.	Develop an understanding of VR technology.	Ages 10-15	HMD (stereo)	Assess impact of gender, race, and scholarship on ability to work creatively and enjoyably	Pacific Science Center, Creative Technology Camp	Summer 1992

Table 11. Characteristics and Usage of Student Development of Virtual Worlds (continued)

Organization	Class/Course	Tasking	Learning Objectives Supported	Intended Audience	Display	Usage	Students' Organization	Date of Use
University of Washington, HITL (continued)	Course on HIV/ AIDS prevention	As a group, build a world that teaches about the dangers of AIDS and the precautions that can be used to protect against it. (With HITL staff support.)	HIV/AIDS awareness.	High school	HMD (stereo)	Assess effectiveness for "at-risk" students and VR's role in a curriculum	Southwest Youth and Family Services School, Seattle, WA	Spring 1993
	Special project (Puzzle World)	Build 3D puzzle pieces that fit together on an individual and group level.	Development of 3D spatialization skills.	Neurologically impaired students, ages 11-14	HMD (stereo)	Evaluation of VE building for cognitive development and spatial processing enhancement	Children's Institute for Learning Differences, Bellevue, MA	1993
	Wetlands Ecology	Study a wetland life cycle: either water, carbon, energy, or nitrogen. Working in groups, develop a virtual world that demonstrates understanding of the wetlands cycle studied, using behavioral models to represent key concepts. Then experience that virtual world and one demonstrating some other wetlands cycle.	Understanding of wetlands ecology.	Grade 7	HMD (stereo)	Comparative effectiveness of building and visiting worlds, and traditional instruction	Kellogg Middle School, Shoreline School District, WA	Fall 1994
						VRRV demonstration	VRRV participants	1995 - 1997
	VRRV Entrée	Students follow 4-step world-building process: planning, modeling, programming, and experiencing a VE. (With HITL staff support.)	Experiencing VR technology in the context of a specific curriculum.	Middle and high school	HMD (stereo)	Evaluation of VR limitations/ potentials, and whether VE building helps learning	14 high schools and middle schools in WA	1994 - 1997
		A a group, extend a basic Tree World with animals that live in the tree or around it, and the things these animals need to live.	Experiencing VR technology.	Grade 4-6	HMD (stereo)	Experimental	Elementary schools in WA	1994
						VRRV use	VRRV use	1994-1997

Another effort that is not discussed at this time because actual development has not yet started is one by Educational Service Unit #3 in Nebraska. This group is the Internet Service provider for regional schools and regards VR and Web technologies as mutually compatible. One of its goals is for students to develop a variety of skills that will allow them to build worlds collaboratively over the Web. To achieve this goal, staff are developing a curriculum for use by area teachers that will help them integrate 3D computing using a low-cost VR development system into their classroom curricula. A Level 1, seven- to eight-day middle school industrial tech module has been developed that provides students with a chance to learn the *x*, *y*, and *z* coordinate system, navigation, and world design skills. Level 2 modules will focus on problem solving skills. An example of a type of problem that might be used in a Level 2 module would be the situation that faced the Apollo 13 ground crew when they had to fix a problem with CO_2 buildup using only the resources available in the spacecraft.

3.2.1 Type of Use

Unlike the pre-developed applications which were roughly equally split between practical use and research vehicles, only about one-third of these efforts are regarded as primarily research oriented. As is shown in Table 12, the majority of the student development of virtual worlds has been conducted as a practical part of a curriculum.

Table 12. Classification of Applications

Practical Use	
EDTC 6242	Exploring Literature Class
Unit on Antarctica	Math Class
Unit on Sports (Stadium)	Computer Programing Class
Language Program	Atomic/Molecular Structure Class
Virtual Museum	Energy Conservation Class
Virtual Stage	VRRV/Washington Entrée
Virtual Cemetery	
Research Vehicles	
Virtual Pyramid	Summer Camp '92
Mathematics (3D Shapes)	HIV/AIDS Prevention Course
Historical Home	Special project (3D puzzle)
Summer Camp '91	Wetlands Ecology

The first student development of virtual worlds as part of classroom activities began in 1993 at Kelly Walsh High School. By the end in 1996, twelve such efforts had been conducted. This fact does not imply, however, any widespread nature of these efforts, because two thirds of the efforts were performed at Evans Bay Elementary School or by the University of Washington's HITL. Indeed, the extent of VR use at Evans Bay Elementary School is remarkable since the teacher leading the VR activities is working independently and his equipment is all self-funded. The efforts at Evans Bay Elementary School are all primarily practical in nature, whereas the HITL efforts are all research oriented.

Not all of the practical efforts have been one-time events. The math and computer programming classes at Kelly Walsh High School, East Carolina University's EDTC 6242, and Haywood Community College's Exploring English Literature course are ongoing programs. Also, Evans Bay Intermediate School expects to continue using its VR-based Language Program.

3.2.2 Educational Topics Supported

There have been fewer instances where students developed virtual worlds than pre-developed applications, and these virtual worlds do not cover the same breadth of educational subjects. Even so, the range of topics covered is impressive and demonstrates the flexibility of VR technology, as shown in Table 13. In this category of student-development of virtual worlds, only the work at H.B. Sugg Elementary School has been reported as supporting specific state curriculum objectives. In this single case, topics in the North Carolina Standard Course of Study Objectives 2.1, 2.2, and 2.3 were addressed.

The scope of student world development efforts varies greatly in terms of the need to research underlying concepts, design and build a world, and support useful viewing of that world. The amount of teacher or researcher support that students have needed in their world-building activities has depended on the complexity of the case in hand and any prior experience the students have. At one end of the spectrum, students at Evans Bay Elementary School now work in groups without support to develop desktop virtual worlds. Projects such as the HITL's Wetlands Ecology represent the other extreme, where students with only a minimal exposure to VR technology (through the VRRV Hors d'Oeuvre program) were provided with extensive support in the design and construction of immersive worlds.

Table 13. Educational Subjects

Ancient Structures	Virtual Pyramid
Communication Technologies	Unit on Antarctica, Unit on Sports (Stadium)
Education	EDTC 6242, Computer Programming Class
Environmental Science	Wetlands Ecology, Energy Conservation Class
History	Historical Home, Virtual Cemetery
Language	Language Program
Literature	Exploring Literature
Mathematics	Math Worlds, Mathematics (3D Shapes), Virtual Stage
Science	Atomic/Molecular Structure Class
Social Science	HIV/AIDS Protection
Spatial Relations	Special project (3D Puzzle)
Study Skills	Virtual Museum
Various	Summer Camp '91 and '92, VRRV Entrée

Most of the worlds have been developed by groups of students, rather than individual students working independently. Although many have been simple walkthrough worlds without much interaction, several worlds have supported a variety of user activities. The actual world development activities themselves have taken from a few days to a few weeks of elapsed time. Except for the work of the HITL, who transported needed equipment between schools, all these efforts employed equipment routinely available in the classroom.

3.2.3 Integration into the Curriculum

Teachers have had a variety of educational goals in encouraging students to develop their own virtual worlds. In the work discussed here, Kelly Walsh High School has been the first school where students developed virtual worlds as part of their regular classroom activities. In math classes, VR technology is used to support pre-calculus and geometry instruction. One activity requires students to build worlds where they can learn to plot 3D coordinates, and another requires them to create geometric shapes to learn about angles and distances. More complex activities are also undertaken, for example, where students are required to create a world that models volumes of revolution. One of the goals of computer programming classes is to learn about VR technology itself, and for their final project, students are tasked to research an area in education where they feel VR technology would help students to learn the content. They then create an educational world around this idea, producing virtual applications that are often used in subsequent classroom activities. Examples of some of the virtual worlds that have been developed include a world to model physical changes in molecules (water to ice and back), a world to model chemical changes of molecules (wood, coal, diamonds), a world to reenact WWII battles, a world that teaches about the Titanic, and a world that provides a walkthrough of a built to scale house plan created for a geometry class.

As previously mentioned, Evans Bay Elementary School is one of the places where the most student-development of virtual worlds has so far occurred. In New Zealand, the national curriculum pays special attention to communications technologies and includes programs aimed at meeting objectives from various skill and content areas. At Evans Bay Elementary School, some of these requirements are being met by using VR as a tool for presenting the results of research efforts. Initially, VR technology was used to support units on Antarctica and sports. (The first of these was summarized in Figure 6 on page 43). In the second case, as part of their study on sports, students examined a local debate as to whether or not the city council should build a big sports stadium or upgrade the sewage system. To aid in their discussions, some of the students developed a virtual sports stadium. Later work looked at how oral and written language skills could be enhanced by encouraging students to explore new ways of expressing their ideas. In this case, students worked cooperatively to create virtual environments and develop stories within them. One group of students created a walkthrough of the attic described in *The Diary of Anne Frank.* Another group constructed a world where the participant finds himself alone in a futuristic prison and has to find out what has happened. The story involved a complex hoax that fooled the prison warden into evacuating the prison.

More recently, in a math class at Evans Bay Elementary School, students were tasked to develop set designs for a school performance of an abridged version of Macbeth. The staging units available to work with were large wooden cubes and platforms of varying sizes. As shown in Figure 8, the instructions required the students to work to scale, documenting their work appropriately in their math books. Other efforts have included the creation of one virtual world to present research information in a museum layout, and creation of another world to present a classification and fitting epitaphs for famous and infamous people in history [Carey 1996a].

Another practical effort involving student development of virtual worlds is ongoing at Haywood Community College, as part of the Exploring Literature in VR course. The objectives of this course are to explore how writers use words, images, symbols, and settings to create a mood, develop characters, and dramatize a story's theme or focus; discover the possibilities that

Extension Maths

The set for Macbeth: We are staging our abridged version of Macbeth and need a series of set designs to consider. We want you to prepare three design possibilities. The scene that you will be considering is the witches scene attached to the back of this briefing sheet. Take note of the requirements of the scene. Where will actors enter from and exit to? Where will they stand?

You have all used the VRML software to design things. This time you will use it to scale and I will be wanting to see evidence that all the work has been done to true scale. You will need to show me written work in your math books - where you will draw sketches and record measurements.

Begin by measuring the Multimedia room accurately.

- What scale will you use?
- How will you ensure that your measurements are accurate?
- How will you measure the ceiling height?

Also measure the staging units that are in the media room. There are three different types.

Now use the VRML to build the media room. Put the preferences to centimeters and save this as the default. As you work in any view there is a constant feedback of actual measurements.

Build the staging units in VRML to the same scale and keep these separate from the room.

Now save the file several times on the hard drive but give it different names, e.g. plan1, plan2, plan3.

Go to the first file and lay the staging units into the media room. Position them carefully and then place avatars at the positions they would be standing in at asterix #1 on the script.

Now go to the second file and lay the room out differently. Position the avatars for asterix #2 on the script.

Repeat the process for asterix # 3 on the script.

Figure 8. Student Tasking for Development of a Virtual Stage

VR offers for providing a new perspective on a literary work; become acquainted with various VR tools and strategies so that fictional worlds can be constructed; and freely express reactions to a literary work and VR both in class discussions and in writing. The course requires students to develop simple walkthrough worlds that depict major events in assigned stories. Examples include scenes from *My Kinsman, Major Molineux* by Nathaniel Hawthorne, *The Yellow Wall-Paper* by Charlotte Perkins Gilman, and *A Jury of Her Peers* by Susan Glaspell.

East Carolina University provides instruction in how to use VR technology as an educational tool. As part of a new VR concentration in the Master of the Arts in Education Degree program, Course 6242 requires students to work with local teachers to identify a useful context for using VR, develop the application, and then conduct a practical evaluation. So far, this course has only been offered as a self-study class. While some students are currently enrolled, none has yet completed the course.

Other efforts have been research oriented, investigating questions such as how student development of worlds improves recognition and manipulation of 3D shapes, helps students understand scientific concepts, or simply improves student motivation and general class performance. Some of these efforts integrated world development into regular class activities and others used special projects. The HITL has conducted most of this research, generally using special projects. Examples include the VR program at the Pacific Science Center Summer Camps in '91 and '92, a special course on Human Immune Virus/Acquired Immune Deficiency Syndrome (HIV/AIDS) protection, and the VRRV Entrée program. These researchers have supported students in developing virtual worlds meeting many themes. Examples of worlds created by the students include Planetscape!! where two characters move with the participant through a futuristic landscape, and Virtual Valley where a visual depiction of a valley enclosed by mountains is supported by audio that reflects, for example, when an object is grabbed. In Summer Camp '92, students tasked to develop a virtual world along an emotional theme developed worlds called Peaceful Rainforest Peaceful, World Emotion, World Relaxation, Spike World Intense Fear, Inca City Precarious, Free Space Free, Space Paradise Terror/Joy, and Future Dreams Relaxation/Confusion/Curiosity. As part of the VRRV Entrée program, students developed a virtual world consisting of a space station where waste materials can be recycled, and a rain forest where over-exploitation results in ecological disaster. The HITL Wetlands Ecology work at Kellogg Middle School straddles the line between a special project and regular class activities. This effort served as a VRRV pilot project and was designed to test researchers' assumptions about the educational value of bringing VR technology to students. The focus of this effort was to compare a constructivist pedagogical approach, using VR technology, with traditional types of classroom activities.

Teachers and researchers at H.B. Sugg Elementary School, James Cook University, and the Slaton Independent School District have all incorporated research activities into the regular curriculum. In their math class, students at H.B. Sugg Elementary School created and manipulated virtual pyramids as part of an investigation into whether such activities could improve students' ability to compare, classify, and draw pyramid shapes. Researchers from James Cook University used students in a primary school math class to help them look at the effectiveness of virtual shape creation and manipulation in improving students' ability to recognize and draw various 3D shapes. At Slaton High School, VR technology has been used in two separate efforts. In the first, students researched atomic and molecular structures and then developed virtual worlds demonstrating the structure of a selected atom or molecule. In the second effort, students selected a particular geographical location where they would like to live and researched its climate, natural flora and fauna, and various other conditions relevant to living in that area. They then demonstrated their understanding by developing virtual worlds that provided walkthroughs of houses designed to pay special attention to energy conservation in heating and cooling.

3.2.4 Support for Students with Special Needs

The only identified effort that has considered how student development of virtual worlds could support education for students with special needs has been conducted by the University of Washington's HITL.

This research effort looked at how development of a virtual world could enhance spatial processing skills in neurologically impaired children or, more specifically, at abilities in spatial relations, sequencing, classification, transformation and rotation, whole-to-part relationships, visualization, and creative problem solving. The work was conducted as a special, one-week intensive VR class at the end of the students' regular summer school program. Students were given a workbook containing schedule information, visualization exercises, a reference card for the software used to build the 3D objects, a set of 3D exercises, drawing paper, and writing paper for making journal entries. Each day was divided into activity and thinking periods, with the first two days including several group discussions. The children chose to work largely independently, each creating puzzle pieces for an individual world. These objects were then combined by HITL researchers in an overall virtual world that the children could visit.

3.2.5 Hardware and Software Issues

For each of the efforts where students develop virtual worlds, Table 14 and Table 15 summarize key aspects of the hardware and software platforms used. As would be expected under the constraints of available financial resources, the majority of student world development has been conducted on desktop machines, both PC and Macintosh computers. The

Table 14. Hardware Support for Student-Developed Worlds

Organization	Platform				Display					Special I/O	
	SGI	Division Workstation	PC	Macintosh	Monitor	Monitor w/ Shutter	HMD	Projection Screen	CyberScope	Spatialized Sound	Hand Device
East Carolina University			✓	✓	✓	✓	✓				✓
Evans Bay Intermediate School			✓	✓	✓						
Haywood Community College			✓				✓	✓			✓
Kelly Walsh High School			✓			✓	✓		✓		✓
James Cook Univ., School of Education			✓	✓	✓						✓
Slaton Independent School District	✓		✓	✓		✓		✓			
University of Washington, HITL	✓	✓	✓	✓			✓			✓	✓
H.B. Sugg Elementary School				✓	✓						

situation has been a little different with the HITL work where researchers visited summer camps or various schools. Citing the lack of appropriate general use software, these researchers had students develop virtual object models and behaviors on standard classroom computers using Swivel-3D. They then took these world components back to the HITL where they were combined to form worlds, and the students then travelled to the HITL to experience these worlds.

Again, probably driven by cost concerns, a much smaller proportion of the efforts employ HMDs compared to the prevalence of HMDs with pre-developed educational VR applications. Only half of the efforts used HMDs, the remaining efforts rely on desktop monitors either with or without shutter glasses. Two efforts (one using an HMD and the other shutter glasses) also used a projection screen and passive glasses as an alternative viewing mode.

Another way in which these efforts differ from pre-developed applications is in the reliance on the visual display. There is no evidence of speech I/O or haptic displays. The HITL did use spatialized sound in one session of the Summer Camp '91 effort when two students returned for a second session. Although these students were successful in their use of the technology, the amount of effort required by both the students and the researchers prevented its continued use in later sessions. The only specialized hand input devices used are wands or joysticks. There are probably several reasons for this minimal use of special I/O devices. Likely the most important factor is that extra skills are required to utilize specialized devices, and students cannot be expected to master these extra skills in the limited time they generally have available for developing virtual worlds. The fact that these devices also require additional processing resources, quite significant resources in some cases, could also be very relevant.

Table 15. VR Development Software for Student-Developed Worlds

Organization	Superscape /VRT	Virtus WalkThrough/Pro	VRDS	REND 386	VRML	Other
East Carolina University	✓	✓	✓			
Evans Bay Intermediate School		✓			✓	✓
Haywood Community College	✓					
Kelly Walsh High School			✓	✓		✓
James Cook University, School of Education		✓	✓			
Slaton Independent School District		✓	✓			
University of Washington, HITL						✓
H.B. Sugg Elementary School		✓				

Virtus WalkThrough and VRDS are among the least expensive VR software development packages for which support is available. They are also primarily focused at the PC level and relatively easy to use. Accordingly, these packages have been the most popular choice for student use. It will be interesting to see how increased use of more powerful PCs, or graphical workstations, impacts this balance over the next few years; that is, whether the benefits of ease of use and low cost continue to outweigh the increased development power offered by more expensive products. Researchers at James Cook University, School of Education, are conducting an informal study looking at the ease of use of Virtus WalkThrough and VRDS for 6th and 7th graders. When VREAM's new product, VR Creator, becomes available, these researchers expect to compare the ease of use of Virtus WalkThrough Pro and VR Creator. Other software used to support student development of virtual worlds includes Design it3D, 3D Design Center, MacroMedia, Extreme 3D, and Hyperstudio.

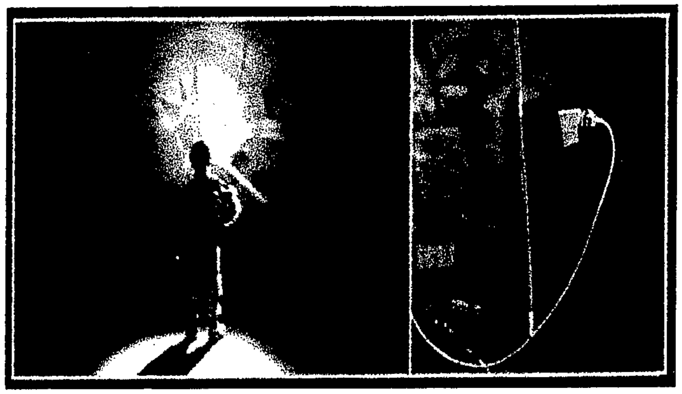
Among the efforts discussed here, VRML has only been used by students at Evans Bay Elementary School. Its use at this school, however, has been fairly extensive and supported by the Virtus VRML 1.0 software development package [Carey 1996b]. Once students had familiarized themselves with this software, they began using VRML as a medium for research presentations in several projects. This usage is still classed as exploratory, but the results so far are encouraging; see Section 4.2 for data on evaluations of these efforts.

3.3 Multiuser, Distributed Worlds

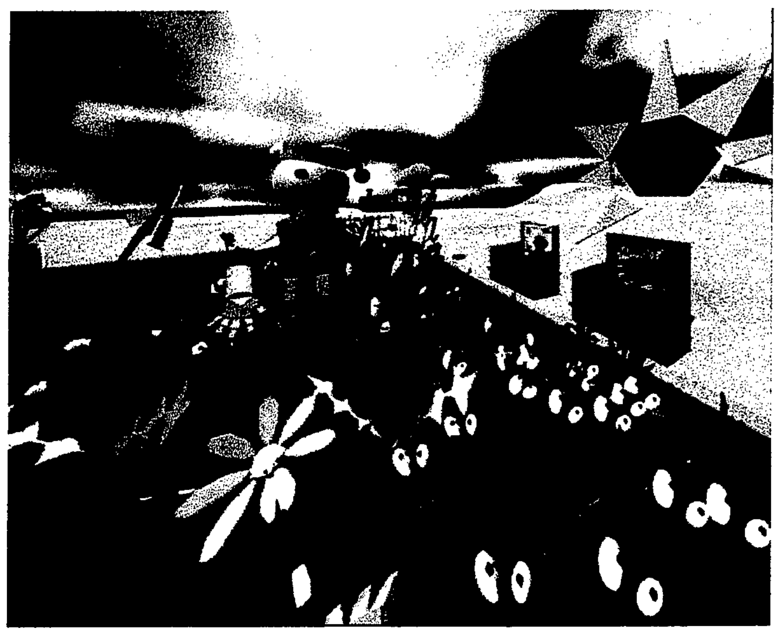
In this section, the Narrative, Immersive, Constructionist/Collaborative Environments for Learning in Virtual Reality (NICE) and Virtual Physics applications are used as illustrative examples of the type of work being conducted with multiuser, distributed educational VR applications. These examples are shown in Figure 9 and Figure 10. The NICE project is a joint development effort by the Interactive Computing Environments Laboratory and the Electronic Visualization Laboratory at the University of Illinois at Chicago. The primary goal of this effort is to study the effectiveness of a virtual environment as a conceptual learning and evaluation medium. The Virtual Physics application is being developed by researchers at the University of Lancaster in England, working with colleagues at University College London and Nottingham University, on the Distributed Extensible Virtual Reality Laboratory (DEVRL) project. In this case, researchers have been focusing on issues of collaborative learning. Since only three applications in the category of multiuser, distributed educational VR applications are discussed, NICE and Virtual Physics come close to defining the entire field. A summary of the characteristics and usage of these three applications is given in Table 16.

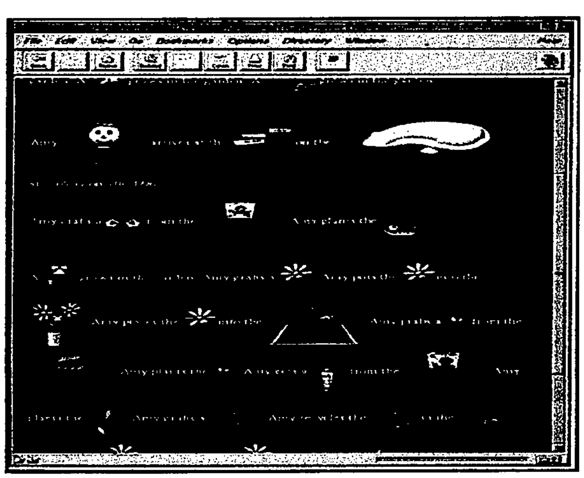
As in the previous sections, only information for those VR applications that have been developed or are currently under development is presented. However, it is useful to note some plans for future development of multiuser, distributed educational VR applications. Researchers at the SIMLAB at Carnegie Mellon University are planning the development of an application called Collaboratory; they expect to work with educators and the Massachusetts State Board of Education to develop a series of virtual worlds that will support collaborative learning to meet curricula objectives in math, science, art, and music. The series of ScienceSpace worlds is planned to be extended to support multiple users to enable research into

Project Goal: To create a virtual learning environment that is based on current educational theories of constructivism, narrative, and collaboration, while fostering creativity within a motivating and engaging context.



NICE Description: The setting is a virtual island where children can search for empty space and build their own ecosystems. Symbolic representations of various environmental elements are used to facilitate childrens understanding of complex ecological interrelationships. The microworlds evolve over time with plants growing and animals populating newly formed ecosystems or migrating to other areas. In addition to planting seeds and manipulating such variables as rainfall (by pulling a cloud over the land they want to water), students can scale and position parts of an ecosystem or factor time to observe quickly and directly the effects of changes they make. Stories that are created while interacting with the virtual world are automatically parsed to look like a picture book and placed on a Web site. Avatars represent the group of children in each CAVE. These have separate hands, body, and head that are mapped to a child's arm and head to allow gestural interaction between participants as well as object selection and manipulation. Students can see their avatar bodies reflected, e.g., in water. Intelligent guides or genies provide guidance (e.g., a talking signpost) or follow the children around sharing knowledge (e.g., Sofia the friendly owl). Teachers can assume the role of genies in a manner transparent to other participants.



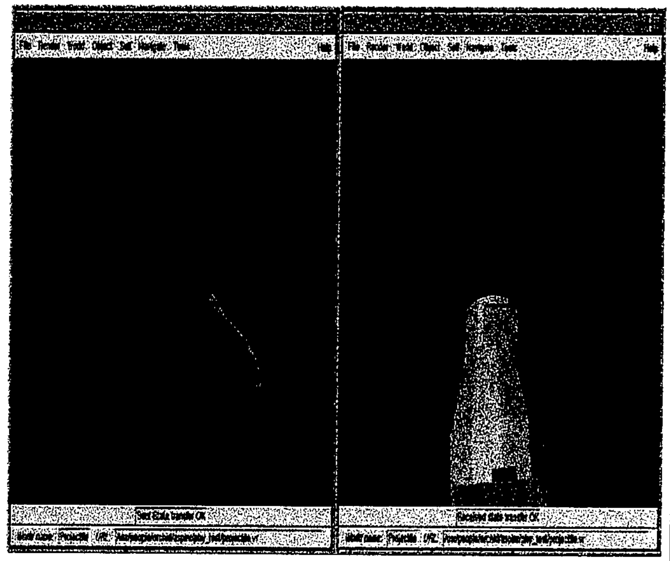


Focus of Current Work:
- Evaluation studies, including the creation of a real garden by children participating in school and community projects, in combination with the collaborative construction of the virtual ecosystem.
- Refine the interaction.
- Develop an authoring tool, in the form of a simple visual language, to provide a user-programmable environment.
- Investigating issues of self-representation and nonverbal communication.

User-Programmable Environment: Will allow, for example, children to define a model of humidity and growth for a particular plant or ecosystem, or construct new imaginary plants with their own set of rules.

Figure 9. NICE

Project Goals: To investigate how collaborative virtual worlds can be designed to provide improved support for conceptual learning of physics.

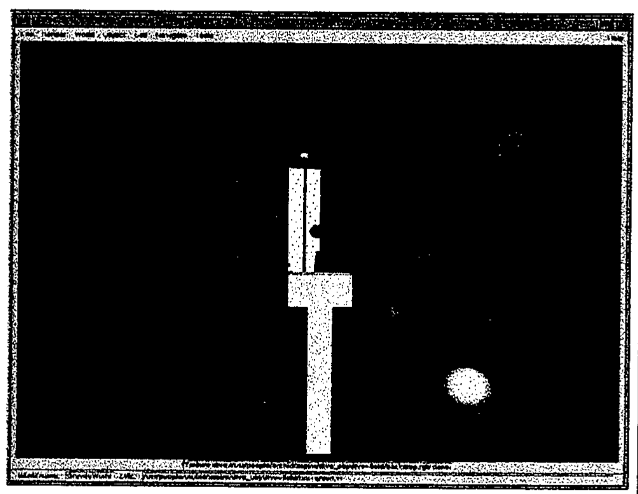


Virtual Physics Description: A number of scientific worlds can be entered from a central space. These worlds have been selected as providing motivation for collaboration. Current worlds and their associated tasks are:

- Cannon World. World consists of a wall, target, cannon with adjustable firing positions, and cannonballs that are acted on by a uniform gravitational field. One participant is placed next to the cannon, and the second linked to the cannonball. The task is to hit a target when the participant by the cannon cannot see it.
- 3D Pivot World. World consists of a table resting on a pivot (so that it moves in the x and z dimensions), and a number of objects of differing masses lying on the table. The task is to level the table by moving the objects.
- Friction World. World consists of a snooker table with 10 differently colored balls rolling around. Unlabeled sliders control the extent to which the world obeys the laws of Conservation of Momentum and Conservation of Energy. Users can also adjust the elasticity of balls and coefficient of friction between table and balls, and induce impulse forces and repulsion forces between the balls. The task is to adjust the environment so that the world behaves in a "real" manner and decide what the unlabeled controls do.
- Bowls World. World consists of a bowling green, a ramp for which slope and direction can be changed, jack ball, and three bowls for each player. Two sliders control the acceleration due to gravity and the frictional coefficient of the green. Task is to roll bowls down the ramp to try and position them as near the jack as possible, building an understanding of the relationship between friction and weight.

Physics Laboratory (under development):

- Provides empty lab where users can perform a predefined experiment or define and conduct their own experiments in order to investigate phenomenon.
- User enters an empty lab and selects from available objects. Behaviors are also selected and used in their initial forms (real-world physics) or adapted to an imaginary world.
- Behaviors are expressed in mathematical format as functions that amend object properties. They may be built up in layers for each object.
- The lab has its own set of properties (e.g., gravity) which may be adapted in the same manner, thus providing a set of laws for overall lab behavior.
- Modes of intended use include students collaborating on some investigative experiment and using the lab as a communication tool for demonstrating rather than describing physical/mechanical models.



Focus of Current Work:

- Development of communication interfaces that integrate effectively with simulations of the physical world.
- Study of how behavior is handled in the Physics Laboratory to guide development of next generation VR toolkits.

Figure 10. Virtual Physics

Table 16. Characteristics and Usage of Multiuser, Distributed VR Applications

Developer	Application	Description	Learning Objectives Supported	Intended Audience	Display	Usage	User Organization	Date of Use
Computer Museum	Network Racer	A game where 3 people work cooperatively to move a packet of critical information from Boston to Sydney across a network, choosing different routes and communication methods. There are 3 stations: 2 net racers and 1 map user.	Explain networking concepts such as how data moves through many computers and how this is affected by speed of connections.	All ages	Desktop	Exhibition (part of The Networked Planet Exhibit)	Computer Museum, Boston, MA	1994 onward
University of Illinois at Chicago, Interactive Computing Laboratory and Electronic Visualization Laboratory	NICE	Participants explore a fantasy island with a range of soil, altitude, and weather conditions. They decide where to plant and populate, collaboratively crafting stories by building small, local ecosystems (such as vineyards and rainforests) and monitoring them as they develop. The world can continue to develop even when there is no interaction.	Engage children in constructing models, say, for ecological interrelationships, and see effects of changing model attributes.	Ages 6-10	CAVE w/ Glasses	Demonstration	SIGGRAPH '96, New Orleans, GA	August 1996
						Evaluation of usability and educational effectiveness	Elementary school in Urbana, IL, Oak Park School and hispanic community activities in Chicago, IL	1996 ongoing
						Demonstration	ThinkQuest, Washington, DC	November 1996
						Demonstration	SuperComputing '96, Pittsburg	November 1996
University of Lancaster, Computing Department	Virtual Physics	Number of scientific worlds entered from a central space: 3D Pivot World, Cannon World, Bowls World, Friction World, and Physics Laboratory. A user is assigned a task, such as refining the basic physics of the environment to model the real world (Friction), or defining and conducting his own experiment (Physics Laboratory).	Develop various physics concepts via construction of non-symbolic models.	Ages 16-18, college students	Desktop	Evaluation of: (1) participant interaction, and (2) the level of physical knowledge that can be assimilated	University of Lancaster, various science departments	1996 - 1997

issues such as whether collaboration via users' avatars in a shared virtual world can support a wider range of pedagogical strategies, and whether such environments will be effective learning tools for students who are most motivated when intellectual content is contextualized in a social setting. Researchers at the HITL are extending their Global Change application to support multiple users so that children at Seattle's Childrens' Hospital can collaborate with children in a nearby school. Finally, Learning Sites, Inc. plans to support distance education and distributed education with its Vari House application. The application will be made available over the Internet and on CDs so that remote instructors can teach an entire class in which all participants are immersed in a virtual world.

Teachers using VR technology at Evans Bay Intermediate School are hoping to set up a virtual classroom, building on the concepts and work of an earlier project that looked at telecommunications-enabled linking of learners. At the Correspondence School in New Zealand, teachers also are intending to develop a virtual classroom application that supports, in this case, second language learning.

3.3.1 Type of Use

There is little practical use of multiuser, distributed educational VR applications to report. The only application that has seen such use, Network Racer, has been available as an exhibit at the Boston Computer Museum since October 1994. No additional venues for this application are expected. The developers of the Virtual Physic application are seeking funding to develop a practical use version of their application, but have no firm plans for such additional work at this time. Whether NICE is expected to transition into practical use at some time in the future is not known.

Table 17. Classification of Applications

Practical Exhibition Use
Network Racer
Research Vehicles
NICE
Virtual Physics

3.3.2 Educational Subjects Supported

Table 18 shows the different topics that this small group of efforts support. As can be seen, they all focus on science education rather than the arts.

Table 18. Educational Subjects

Environmental Science	NICE
Data networking	Network Racer
Physics	Virtual Physics

3.3.3 Pedagogical Support

These applications all involve more than student walkthroughs of a virtual world. Instead, students are required to actively collaborate in the virtual experience, often taking different roles. For example, in the Network Racer application, three participants can change between roles of a net racer and a map user in playing a game involving moving critical data across an international network. This game is intended to support learning basic networking concepts. Table 19 lists the different types of pedagogy supported by the three applications discussed in this section.

Table 19. Type of Pedagogical Support

Network Racer	Guided-inquiry
NICE	Story-building, guided-inquiry, collaboration
Virtual Physics	Guided-inquiry, collaboration

NICE and Virtual Physics both have strong pedagogical underpinnings that support investigating the capabilities of collaborative VR as a learning tool. NICE embodies principles of constructivism, collaboration between real and synthetic users, problem solving, and authentic experiences to support a distributed participatory theatre [Roussos et al., 1997]. More specifically, constructivism is supported by activities that teach concepts involved in the creation and maintenance of small local ecosystems. Students explore an island and select open land to plant and populate. The behavior of different types of flowers, trees, plants, and animals in these ecosystems is based on rules that, for example, dictate what happens to a particular plant when it is close to other plants and given certain amounts of sunlight, rainfall, and weeding. Each ecosystem continues to develop in the absence of the students at a predetermined rate. The collaborative element of NICE allows students, or groups of students, working on separate VR systems to interact in their different activities. Students can also interact with intelligent guides, called genies, that not only provide information but interact with the students to help them make decisions. Narrative plays a major role in NICE. As the students construct their ecosystems, and even when events occur during the students' absences, every action is recorded in the form of simple sentences, such as "Amy pulls a cloud over her carrot patch and waters it." This recording is then parsed, replacing certain words with representative icons so that the end product is a form of storybook. These books are made available on the students' Web pages, and students can take home the story and reflect on it.

The approach taken for Virtual Physics was different. Again using principles of constructivist learning and collaboration, the individual Virtual Physics worlds are each designed to support the participants in cooperatively developing non-symbolic models of the relevant physics concepts [Brna and Aspin, 1997]. This use of collaboration is based on previous work investigating the educational utility of collaboration, in particular the importance of maintaining a group's mutual understanding of the set of goals and how these may be solved [Roschelle and Teasley, 1995; Burton and Brna, 1996]. The initial set of worlds in Virtual Physics was specifically selected to motivate collaboration by providing students with tasks that were difficult to perform independently. The most recent work focused on the development of a Physics Laboratory for the Virtual Physics application. Using this new world, researchers started to investigate issues in modeling behaviors in virtual worlds. The researchers hope to continue investigating issues of collaboration and conceptual learning, and to continue looking at topics such as how the interaction between representational fidelity, immediacy of control, and presence impacts conceptual learning.

3.3.4 Hardware and Software Issues

The networking methods these applications use are of particular interest. Virtual Physics uses support provided by the Internet and this most likely represents the trend of future multiuser, distributed educational VR applications. NICE, on the other hand, is built on the Graphical User Learning Landscapes in VR (GULLIVR) architecture that allows multiple GULLIVRs running on separate VR systems to be connected via a centralized database that ensures consistency across the environments. Multicasting is used to broadcast positional and orientation information about each avatar, and the Transmission Control Protocol/Internet Protocol (TCP/IP) is used to broadcast state information between the participants and the behavior system. A Java interface is currently under development to allow children with access to the Web to use a special 2D version of NICE to interact with participants using CAVEs. A simpler approach was taken for the Network Racer by exploiting the shared disk capabilities of Windows for Workgroups 3.1 to build an application that would survive the loss of individual nodes at runtime.

A summary of the hardware platforms, displays, and special I/O devices used by these applications is given in Table 20. Perhaps reflecting their intended use as practical applications or research vehicles, Network Racer uses PCs, while the other two efforts both employ SGIs.

Table 20. Hardware Support for Multiuser, Distributed Worlds

Developer	Platform		Display			Special I/O	
	SGI	PC	Monitor	HMD	CAVE w/ Glasses	Speech I/O	Hand Device
The Computer Museum		✓	✓			✓[a]	✓
University of Illinois, ICE Laboratory and EVL	✓		✓		✓	✓[b]	✓
University of Lancaster, Computing Department	✓		✓	✓			

a. Digitized speech output only.
b. Speech recognition only.

NICE is one of the few applications that is using a CAVE display to allow several children to participate as a group in a session with the virtual world. Alternatively, participants can use a more limited version of a CAVE (called the Immersadesk) that uses a single projection screen and passive glasses to support stereoscopic viewing. Virtual Physics supports both immersive and desktop use. Network Racer is a desktop application. As yet, none of these applications has included any haptic or spatialized sound displays. There is only limited use of speech I/O (either speech recognition or digitized speech output; no application supports both).

In terms of software support, Network Racer uses WorldToolKit while the others both use less common VR development systems. Virtual Physics was developed using the Distributed Interactive Virtual Environment (DIVE) system available from SICS in Sweden. In addition to supporting the development of immersive, multiuser virtual worlds that can be networked over the Internet, DIVE supports meetings between participants where each is represented by an avatar. NICE is being developed using the facilities of GULLIVR that was designed to run in a CAVE environment.

4. Evaluations of VR Usage

This section reviews the evaluations that researchers and teachers have conducted on their various uses of VE technology. As before, pre-developed applications, student development of virtual worlds, and multiuser worlds are treated separately, in Sections 4.1, 4.2, and 4.3, respectively.

In total, 35 completed evaluations have been performed on the identified efforts. Over 20 additional evaluations are currently underway or already planned. Just as the majority of educational uses of VR technology have involved pre-developed applications, so have the majority of evaluations to date been performed on this category of applications. The proportions of completed evaluations performed in each category of pre-developed, student-developed, and multiuser VR are 24:10:1, showing a higher predominance for evaluations of pre-developed applications compared to those of student-developed virtual worlds. When looking at only the number of efforts in each category that have been evaluated (19:10:1), the proportions change only slightly. Work with multiuser, distributed applications began later than that in other categories which is the primary reason for the low proportion of completed evaluations of this type of application and, indeed, the low number of efforts themselves.

All the efforts that are primarily research oriented have been the subject of at least one evaluation; this, of course, is to be expected. However, while over half of the pre-developed applications in practical use have been evaluated, only two of the eleven identified practical efforts where students developed worlds have seen a similar evaluation. While these figures seem low, it must be remembered that all current educational uses of VR are, at least to some extent, exploratory, and even where no explicit evaluations have been performed the researchers and teachers are forming their own opinions of the value of the technology.

4.1 Evaluations of Student Use of Pre-Developed Virtual Worlds

Information on the set of completed evaluations of pre-developed virtual worlds is given in Table 21. As this table shows, the majority of the pre-developed applications have been used to conduct a single study and then laid aside. Applications that are the focus of a series of ongoing evaluations are Virtual Environment Science Laboratory (VESL), Greek Villa, NewtonWorld, MaxwellWorld, PaulingWorld, LAKE, Makaton World, Life Skills World, and Global Change. At the current time, however, more than one evaluation has only been completed for VESL, NewtonWorld, and MaxwellWorld. Overall, the evaluations have varied widely with respect to

Table 21. Completed Evaluations on the Use of Pre-Developed Virtual Worlds

Performing Organization	VR Application/ World	Purpose of Evaluation	Description	Major Findings
ERG Engineering, Inc.	Cell Biology	Evaluation of impact of immersion (monoscopic) and interactivity on educational effectiveness	Informal study based on interviews and observations. Subjects viewed material using HMD, desktop, or video tape. Assessed impact on symbolic and function retention of human cell organelle information, time spent, enjoyment, and increased interest in subject matter.	- Retention overall was low, but immersive VR performed best for symbolic retention and non-immersive VR best for function retention. - Time spent varied the most for immersive users and was consistently underestimated by both VR groups. - Immersive subjects expressed more enjoyment and greater likelihood of taking a free biology class.
Georgia Institute of Technology, GVU Center	Virtual Gorilla Exhibit	Formative evaluation	Informal study where students were observed interacting with the application, and subsequently asked questions about their explorations.	- VR was an effective tool for its educational objectives, allowing each student to customize their learning experience to best suit themselves while still making sure they were exposed to most important facts. Examples of potential improvements include providing students with an automated guide to answer questions, a representation of a virtual body, and a peer to interact with. - Students experienced a sense of presence and enjoyed their explorations. - Students had some localization problems with constant amplitude sounds.
	CDS	Comparative evaluation of immersive design as a concept and of particular user interface tools	Informal study based on evaluator observations and subject interviews. Graduate students used CDS to help complete a 10-week architectural design project. Compared immersive design to paper or desktop computer-based design. Also noted successes/problems with virtual interface techniques such as virtual pull-down menus, 3D positioning, and navigation.	- Spatial understanding of architectural spaces increased. - Overall productivity was low, but specific interaction techniques showed promise. - Virtual tools adapted from the desktop metaphor were well received and easy to use. - Small changes in position, size, color, or texture were simple to make and provided immediate feedback. - Large changes to geometry and creation of conceptual designs were generally difficult and cumbersome. - A CAD system combining traditional desktop modeling with an immersive option would be useful and allow the strengths of both environments to be exploited.
Interface Technologies Corporation	VESL	Subjective effectiveness evaluation	Informal study where subjects worked with VESL and then completed questions about its effectiveness.	- Students consistently rated lessons positively, a mean of 7.0 (on a 9-point scale). - Teachers gave an overall educational effectiveness rating mean of 7.9, with particularly high scores for the effectiveness in presenting the material (8.7) and potential for integrating VESL in the classroom (8.7).
		Subjective usability evaluation	Informal study where subjects worked with VESL and then answered questions addressing such topics as aesthetics, usability, immersion, update rates, graphics quality, quality of the speech and sound system, and utility of controls.	- Mean ratings were significantly greater than 5 (on a 9-point) scale for each of aesthetics, usability, and immersion. Other aspects rated equally well. The overall mean rating of usability was 6.8.

Table 21. Completed Evaluations on the Use of Pre-Developed Virtual Worlds (continued)

Performing Organization	VR Application/ World	Purpose of Evaluation	Description	Major Findings
Interface Technologies Corporation (continued)	VESL (continued)	Effectiveness evaluation	Used multiple choice pre-/post-testing of knowledge of specific physics concepts. Subjects had use of VESL for 30 minutes between the tests.	- The post-test score were significantly higher that pre-test scores.
James Cook University, School of Education,	Room World	Evaluation of impact of immersion on recall	Used post-testing to assess recall about a simulated scene after exploring that scene vs. studying 18 photographs of the scene.	- VR did not outperform photos in ability to remember objects and object colors, but did outperform photos in ability to recall numbers of each object and object location.
	Great Pyramid (from the Virtus Archaeological Gallery)	Subjective effectiveness evaluation	Pilot study that assessed how exploration of a simple virtual pyramid supported learning about ancient Egyptian pyramids. Used videotape recordings and subject interviews.	- Students reported that books were more successful in teaching about pyramids, stating that the virtual pyramid lacked the detail and life-like textures, whereas they liked the book pictures and explanations. - The major problem was in navigating sloping passage ways. - Students particularly appreciated the ability to see the design view of the corresponding walkthrough area.
North Carolina State University, University of North Carolina Medical School	Street World	Evaluation of whether autistic children could benefit from a VR-based learning environment	Informal study, based on interviews, that assessed 2 autistic children's tolerance of an HMD, ability to identify and follow a car, and ability to move to and stop at a "stop" sign.	- Children were able to navigate in the world and identify objects. They demonstrated learning of assigned tasks.
Oregon State University, School of Education	Spatial Relations World	Evaluation of impact of immersion on spatial problem solving abilities	Formal study based on pre/post-testing. Using VR and desktop Auto CAD, children practiced visualization, displacement and transformation, creative thinking; also the creation, manipulation, and utilization of mental images in solving spatially related problems.	- VR aided development of visualization, displacement, and transformation abilities. Although these can influence spatially-related problem-solving, the evidence to support a relationship between perceived realism was inconclusive.
Sheffield Hallam University	Greek Villa	Educational effectiveness	Field study based on dialog analysis, questionnaires, written reports. Assessed how collaborative exploration of a virtual Greek residence can support learning.	- Early analysis of data indicates that the VR experience did promote "learning talk" between students. Analysis is ongoing.

Table 21. Completed Evaluations on the Use of Pre-Developed Virtual Worlds (continued)

Performing Organization	VR Application/ World	Purpose of Evaluation	Description	Major Findings
University of Houston, George Mason University, and NASA JSC	NewtonWorld	Formative usability evaluation	Informal studies based on observations, thinking out loud protocols, and interviews. Subjects used 4 variations of the interface (menu-based, gesture-based, voice-based, multimodal). Assessed task completion, task times, error rates, simulator sickness rates and nature; and subjective ratings of task difficulties and learner motivation.	- Users were comfortable with the virtual hand and bouncing ball metaphors. - The majority of users had problems navigating. - The majority of users ranked the multimodal interface (voice, gestures, and menus) above the others. - Voice was the preferred interaction method and the most error-free. Menus were also well liked although users had difficulty in selecting menu items. Gestures were unreliable and the least preferred interaction method. - All users reported slight to moderate levels of discomfort/ eyestrain after wearing HMD for approx. 1 1/4 hours. - User comments suggested that the ability to observe phenomena from multiple viewpoints was motivating and crucial to understanding.
		Formative subjective effectiveness evaluation	Informal study based on a survey. Participants viewed a demo and then experienced the world. Survey focused attention on the interactive experience, recommendations for improvements, and perceptions of potential effectiveness.	- A large majority felt that NewtonWorld would be an effective tool, found basic activities easy to perform, and were enthusiastic about 3D nature of learning environment and the ability to observe phenomena from different viewpoints. - Some participants raised concerns regarding limitations of prototype and encouraged expanding activities, environmental controls, and sensory cues provided. - Participants experienced some difficulty using menus, several recommended a broader field-of-view, and some had difficulty focusing HMD optics.
		Evaluation of impact of multi-sensory interface on effectiveness	Formal experiment based on observations, student comments and predictions, interviews, usability questionnaires, and pre- and post-tests. Focused on both the importance of multi-sensory experience and reference frame usage in learning. Used 3 groups of subjects differentiated by controlling visual, haptic, and auditory cues.	- Single session usage was not enough to dramatically improve users' mental models. - Students receiving sound/haptic cues rated the application as easier to use and the egocentric reference frame as more meaningful than those receiving visual cues only. - Students who received haptic cues, in addition to sound and visual cues, performed slightly better on questions relating to velocity and acceleration, but worse on predicting system behavior. - Several users experienced difficulty with eye strain, navigating, menu usage; these problems interfered significantly with the learning task. - Students suggested improving the learning experience by expanding features and representations used, and by adding more variety to the nature of learning activities.

Table 21. Completed Evaluations on the Use of Pre-Developed Virtual Worlds (continued)

Performing Organization	VR Application/ World	Purpose of Evaluation	Description	Major Findings
University of Houston, George Mason University, and NASA JSC (continued)	MaxwellWorld	Formative usability, learnability, and effectiveness evaluation	For usability and learning studied observations, students' predictions and comments, questionnaires, and interview feedback. Formal evaluation of effectiveness based on pre- and post tests. Evaluated the application as (1) a tool for remediating misconceptions about electric fields, and (2) teaching concepts about electric fields. Tested for retention of material over time by conducting a third session approximately 2 weeks after 2 prior sessions.	- Majority of students commented that they felt MaxwellWorld was a more effective way to learn about electric fields than either textbooks or lectures. - The 3D representations, interactivity, ability to navigate to multiple perspectives, and the use of color were cited as important characteristics that aided learning. - Students demonstrated improved understanding of physics concepts, learning, for example, the ability to describe distribution of forces in an electric field, and identify and interpret equipotential surfaces. - Although the world helped students qualitatively understand 3D superposition, they had difficulty applying superposition when solving post-test problems.
		Comparative effectiveness evaluation	Formal experiment based on pre/post-tests and questionnaires. Compared MaxwellWorld to the EM Field computer-based simulator on the extent to which representational aspects (2D vs. 3D and quantitative vs. qualitative) of the simulations influenced learning outcomes. Lessons used utilized only those features of MaxwellWorld that had counterparts in EM Field, thus focusing on electric fields and electrical potential. Impact of multisensory cues (via a haptic vest) in MaxwellWorld was also examined.	- All students demonstrated a better overall understanding of topics on the post-test, though students with an initial moderate knowledge benefiting less than those starting with little or no knowledge at pre-test. More advanced students had difficulty overcoming misconceptions. - In most areas, each group of students performed similarly. The MaxwellWorld group, however, was better at describing the 3D nature of electric fields, potentials, and their respective representations; EM Field students typically restricted answers to a single plane. - Students rated MaxwellWorld as easier to understand, but EM Field as easier to use. MaxwellWorld was rated as more rewarding, stimulating, and informative. - Students who had difficulty with concepts found multisensory cues helped them understand representations. - After 5 months, both groups performed similarly on retention tests, with MaxwellWorld students showing a slight advantage in their ability to describe electronic fields in 3D.
University of Ioannina, Dept. of Primary Education	LAKE	Evaluation of usability, and comparison of navigation devices	Informal study based on questionnaires and discussions. Subjects spent up to 1 hour in a virtual office world and then in LAKE.	- Students preferred using a traditional mouse as the navigation device and did not try very hard to use the other devices (joystick or a spaceball/spacemouse). - Students ranked the mouse higher for ease in learning and use; the joystick and spaceball/spacemouse were ranked the same. - Half the students stated that they had immersive experiences such as "I had the feeling the I was moving in the real world" even in this desktop application.

Table 21. Completed Evaluations on the Use of Pre-Developed Virtual Worlds (continued)

Performing Organization	VR Application/ World	Purpose of Evaluation	Description	Major Findings
University of Michigan, Dept. of Chemical Engineering	Vicher (I and II)	Formative user evaluation (I)	Informal study based on questionnaires. Users answered engineering questions and, after using the Vicher, were given the opportunity to modify their responses; they also responded to general questions about the virtual experience.	- User responses after Vicher were more accurate, more complete, and showed a better understanding of engineering concepts. - Over 80% responded that they felt they had learned something from the experience.
	Safety World	Formative user evaluation	Informal study based on evaluation forms. Users rated model components and the system as a whole, and gave short answers for suggestions on improvements and other feedback. One group evaluated the safety and hazards of the plant from a written description and then evaluated the VR representation. The other group used both the VR experience and the written description in judging the safety and hazards present and then evaluated the VR system.	- Most of the students rated the current value of the system as medium to low, but rated its potential very highly. The same trend was observed for ratings on the help system and HMD usage. - Student rankings on their understanding of the chemical process and its hazards increased as a result of the virtual experience. Across the students, these rankings formed a Bell curve centered between 2 and 3 (on a 5 point scale). - Most common complaint was difficulty in navigation. - Comparison between the 2 groups did not show any significant variations in their evaluations of the model, the equipment, the help system, or the future potential of these.
University of Nottingham, VIRART Group	Makaton World	Pilot study	Informal study looking at how well the system was received by students and teachers.	- While some students had difficulty in exploring the individual warehouses and identifying correct objects in the reward warehouse, most students were able to recognize at least some of the objects in the reward warehouse. - Most of the students recognized the hand signs displayed with each different object and immediately mimicked the sign. - Some students had difficulty manipulating either a mouse or spaceball, preferring to use a touchscreen to point to objects to be selected.
	Life Skills Worlds	Evaluation of skill transfer to real world (Virtual Supermarket) and promotion of self-directed activity	Formal experiment based on examination of performance during training with VE, videotapes of staff and student interactions while using the VE, and pre/ post-testing at a supermarket.	- Students who used the virtual supermarket were significantly faster and significantly more accurate on the return to the real supermarket than those in the control group. - While using the VE, there was a significant decrease over time of teachers' activities. - Teachers' activities decreased at a faster rate for didactic categories (such as instruction, physical guidance) than for more open-ended assistance, such as suggestion. - Students showed a significant increase in learning speed for each of the categories into which their self-directed activities were coded.

Table 21. Completed Evaluations on the Use of Pre-Developed Virtual Worlds (continued)

Performing Organization	VR Application/ World	Purpose of Evaluation	Description	Major Findings
University of Washington, HITL	Atom World	Evaluation of impact of immersion and interactivity on educational effectiveness	Used written and oral pre/post-testing to assess how immersive and non-immersive VR, non-interactive computer program, videotape, and no-treatment control instruction facilitated factual recall and comprehension of principles.	- For recall, the immersive VR outperformed the control group only. - For comprehension, the advantage of VR lay in the interactivity it offered, not in immersion. - For long-term retention, although immersive VR scores dropped from initial post-test level, immersive VR maintained a significant improvement over pre-test scores.
	Zengo Sayu	Comparative educational effectiveness	Used pre/post-testing to assess how VR and non VR-based whole language learning compared with existing computer-based instruction given in English.	- Instruction based in Japanese (Zengo Sayu and the equivalent non-VR instruction) gave a significant performance improvement over the English computer-based instruction.
	VRRV Hors d'Oeuvre	Assess usability and motivational impact of VR educational applications	Used exit questionnaire to assess the ease of use during short experiences with VR, students' enjoyment of the experience, and students' sense of presence.	- Students rated their enjoyment as very high with a negligible number of reports of queasiness. - Difficulty in navigating around the world, and interacting with it, decreased with age. - Enjoyment and sense of presence decreased with age.

their formality. Some have included both informal subjective measures as well as more formal pre- and post-testing.

In general, the types of issues being addressed in evaluations fall into two broad groups: those relating to effectiveness, and those addressing usability. Table 22 identifies the applications evaluated in each category, and shows how these categories can be sub-divided to further distinguish the focus of different evaluation efforts. The remainder of this section follows the hierarchy given in Table 22 to structure the discussion of particular evaluations.

Table 22. Types of Completed Evaluations

Effectiveness Evaluations	
General educational effectiveness	Virtual Gorilla Exhibit, VESL, Greek Villa, NewtonWorld, MaxwellWorld, Vicher (I and II), Safety World
Effectiveness for learning disabled students	Street World, Makaton World, Life Skills World
Comparative educational effectiveness	CDS, Great Pyramid, Zengo Sayu
Impact of immersion	Cell Biology, MaxwellWorld, Spatial Relations World, Atom World, Room World
Usability Evaluations	
General usability	CDS, NewtonWorld, MaxwellWorld, LAKE
Usability for physically and learning disabled students	VESL, Makaton World, Street World
Sense of presence, ease of navigation, enjoyment	Virtual Gorilla Exhibit, Safety World, VRRV Hors d'Oeuvre

4.1.1 Evaluation of Effectiveness

4.1.1.1 General Educational Effectiveness

One of the largest development and evaluation efforts is that being performed on the ScienceSpace series of worlds by researchers at University of Houston-Downtown, George Mason University, and NASA's Johnson Space Center (JSC). The major goal of this work is to examine whether the type of immersion and multisensory communication available from VR technology can help students construct accurate mental models of abstract science concepts and remediate deeply rooted misconceptions about the relationships among mass, force, motion, acceleration and velocity.

The first ScienceSpace world, NewtonWorld, has been the subject of three effectiveness evaluations to date. The first was a subjective educational effectiveness evaluation by 100 physics educators and researchers attending a conference. After watching a 10-minute demonstration of NewtonWorld, these participants were guided through a number of activities and then asked to complete questionnaires. A second, this time formal, evaluation looked at the impact of a multisensory interface (providing auditory and haptic cues in additional to visual cues) on educational effectiveness. Here, in the course of a two and a half to three hour instructional session, students spent one and a quarter hours inside NewtonWorld. During their interaction with the virtual world, students predicted relationships among factors and behaviors of bouncing balls and then compared their predictions to virtual world observations. Analysis of the collected data failed to show any significant increase in knowledge as a result of the instruction, and the researchers suggest that multiple sessions with NewtonWorld may be needed to overcome deeply seated science misconceptions [Salzman et al., 1995b]. With respect to the use of multisensory cues, sound and haptic cues seemed to engage learners and direct their attention to important behaviors and relationships more than visual cues alone. Currently, this group of researchers is conducting an evaluation of the content and lesson structure of NewtonWorld. Additional evaluations that will investigate the impact of age group, ego versus exocentric viewpoints, and, again, multisensory interfaces on effectiveness will be started in the fall of 1997. After these studies, the final version of NewtonWorld is expected to undergo field testing.

The first formal evaluation of the educational effectiveness of MaxwellWorld provided students with three 2-hour sessions in the world and resulted in more positive evidence of the learning effectiveness than was found with single-session use of NewtonWorld [Dede 1997b]. Here pre- and post-tests showed that students improved their understanding of the distribution of forces in an electric field and the use of test charges and field lines. Manipulating the field in 3D appeared to play an important part in this learning. MaxwellWorld helped students qualitatively understand 3D superposition, and though students had some difficulty in applying superposition in the post-test problems, overall post-test performance was good with all students demonstrating an understanding of concepts such as Gauss's Law, field versus flux, and directional flux. A more recent evaluation of MaxwellWorld compared the effectiveness of MaxwellWorld with that of a non-immersive application providing similar functionality; this is discussed in Section 4.1.1.4. The researchers plan to begin field testing the application in 1998.

The work with the ScienceSpace worlds provides the best example of where evaluations have been effectively used to support the development of educational VR applications. This process used what the researchers term a *learner-centered* approach, defined as a special case of user-centered design with the needs of learners and the ability of technology to support the learner taken into consideration. Accordingly, the development process consists of an iterative process of design and evaluation, with the evaluation addressing issues of both usability and educational effectiveness. Table 13, based on data from Salzman et al. [1995a, 1995b], shows how the results of a series of evaluations led to progressive design refinements. A similar cycle of iterative design and evaluation is being performed for MaxwellWorld, and is expected for PaulingWorld. Based on their work to date with the ScienceSpace worlds, the researchers are developing design heuristics, assessment methodologies, and insights that they hope will be generalizable to a wide range of educational environments.

Another application that, like NewtonWorld and MaxwellWorld, has been the subject of a series of evaluations is VESL. The goal of the VESL's developers is to provide an application that can be used by students with physical disabilities, such as cerebral palsy and spinal cord

Table 23. Impact of Findings on Refinement of NewtonWorld

First evaluation—formative usability and learning	
Positive Findings	Negative Findings
- Students work well with the bouncing ball metaphor and catch-throw activities - The virtual hand metaphor worked well - The majority of students preferred the multimodal interface (voice, gestures, and menus) to any single mode - Voice commands were easy to use, most error-free, and preferred method of interaction - Menus were well liked, but selecting items was difficult - Students found that having multiple viewpoints of phenomena was motivating and crucial to understanding - Additional visual, auditory, or tactile cues were needed to smooth the interaction and help focus on important information	- Navigation (by pointing the hand in the desired direction of travel) presented some difficulties - Hand gestures were unreliable and the least-liked interaction mode - The least-liked interface characteristic was the inability to focus the HMD optics - All participants indicated slight to moderate levels of eyestrain and discomfort after using the application for over 1 hour - Students interpreted the size of the ball as a cue for mass, reinforcing the misconception that larger objects are more massive
Changes: - Expanded number of viewpoints from 2 to 5 with a "beaming: method for moving between views - Incorporated a standard navigation training procedure for the introduction to NewtonWorld - Eliminated gesture-based commands and explored feasibility of incorporating voice commands (these were simulated for the experiment) - Provided sound cues to supplement visual cues	
Second evaluation—subjective effectiveness educational evaluation	
Positive Findings	Negative Findings
- A large majority of participants felt that NewtonWorld would be an effective teaching tool - A large majority found basic activities, including navigation, easy to perform - Many were enthusiastic about the 3D nature of NewtonWorld and the multiple viewpoints for observing phenomena	- Many participants experienced difficulty using the menus - Several felt that a broader field-of-view would have improved their experience - Many had difficulty focusing the HMD optics - Several expressed concerns regarding the limitations of the prototype and encouraged expanding activities, environmental controls, and adding more sensory cues
Changes: - Expanded interface to include a haptic vest and more extensive visual and auditory cues - Refined menus to make item selection easier - Changed menu bar to a small 3-ball icon to increase visual field and improve experience of motion	
Third evaluation— impact of multisensory interface on educational effectiveness	
Positive Findings	Negative Findings
- Students appeared more engaged in activities when more multisensory cues were provided - Students receiving sound and haptic cues rated the world easier to use than those receiving visual cues only - The more cues used, the higher the rating for ease of use with which students could understanding what was happening from the egocentric frame of reference - Students receiving haptic cues in addition to visual and auditory cues performed slightly better on questions relating to velocity and acceleration	- Single, short session usage of NewtonWorld did not significantly transform students' misconceptions - Students receiving haptic cues in addition to visual and auditory cues performed slightly worse on predicting the behavior of the system - Several students experienced difficulty with eye strain, navigating, and selecting menu items; these problems interfered with the learning task
Changes: - Moved menu from fixed location in HMD field-of-view to user's second virtual hand - Refining auditory and tactile cues to provide richer information and to allow turning on/off for individual lessons - Expanding NewtonWorld to include a broader range of learning activities	

injuries, as well as by non-disabled students. Accordingly, usability has been a key concern, as is discussed in Section 4.1.2. In terms of educational effectiveness, VESL has been the subject of two evaluations. The first was an informal subjective evaluation where both students and teachers participated [Nemire 1995b]. Both groups rated VESL highly on such topics as educational effectiveness and potential for integrating VESL into the classroom curriculum. In the second effectiveness evaluation, a small number of students were given a 30-minute session with VESL and, based on their pre- and post-test scores, gained a significantly better understanding of the physics concepts covered by VESL.

A formative user evaluation provided researchers at Georgia Institute of Technology's GVU Center with useful information about an initial design of the Virtual Gorilla Exhibit. The goal of these researchers' work is to improve their understanding of how VR can be used as an educational tool to provide general knowledge to children (as opposed to providing task training to adults). The informal evaluation provided feedback that suggested some potential improvements to the application. For example, providing a guide to answer questions and speed the learning process, providing students with a virtual body so they can see themselves in the virtual world, and providing students with a peer to play with instead of just being at the bottom of the gorilla social ladder. At present, the focus of this work is more on the technological side of VR, and user comments and qualitative observations have been used to determine what was working and how well it was working. Future work is expected to look more formally at the educational effectiveness of the exhibit.

The evaluation of Greek Villa is similar to those performed on the ScienceSpace worlds in focusing on pedagogical issues. In this case, the researcher undertaking the work is interested in using VR to encourage group working and, in particular, is using VR to investigate the possible role of "learning talk." Accordingly, the informal evaluation of Greek Villa focused on the communication between students, and the results indicate that learning was apparent in the talk that took place within the groups using VR [Grove 1996]. Further evaluation is expected to investigate these issues more formally.

The development of the Vicher and Safety World applications at the University of Michigan has been part of a research effort that has three goals:

- Providing educational modules with as much practical use to as many students as possible.
- Determining what educational situations in engineering will benefit most from VR technology, and
- Developing techniques for the display of, and interaction with, scientific and technological information.

The program of evaluations underway and planned for the Vicher and Safety World applications is designed to support these goals. The initial evaluation of each of Vicher I and

Safety World were formative in nature, that is, intended to guide further development of each application. For Vicher I, students completed a questionnaire soliciting answers to specific engineering questions both before and after exposure to Vicher, and also provided some general information about the virtual experience [Bell and Fogler, 1995]. User responses after the experience with the virtual world were more accurate and more complete, and showed an improved understanding of the pertinent engineering concepts. Most of the students felt that they had learned through the experience. One feature that was particularly appreciated was the 3D color graph of reaction kinetics and its relationship to the packed bed reactor; students cited this graph as an example of how the virtual world gave them a more tangible grasp on the meaning behind the relevant equations. In the case of Safety World, students conducted a safety and hazard analysis using the virtual world and then completed evaluation forms [Bell and Fogler, 1996]. While students' analyses continue to be studied, initial findings are available. Students ranked the current value of the safety world simulation, help system, and HMD usage as quite low but, in each case, over 75% of the students saw potential values as 4 or 5 on a 5-point scale. The applications were refined based on the feedback received from these evaluations and data from the next two formative evaluations (this time including Vicher II) are already being analyzed. Meanwhile, off-site beta testing has begun.

In addition to the ongoing and planned evaluations of the ScienceSpace worlds, Vicher I and II, and Safety World already mentioned, other evaluations of educational effectiveness are currently underway. The HITL is completing data analysis on the evaluation of the educational effectiveness of its Global Change application, field testing of Vari House is being conducted, and Crossing Street is being used to assess the transfer of skill-related knowledge gained in a virtual world to the real world.

4.1.1.2 Effectiveness for Learning Disabled Students

The VIRART group at the University of Nottingham has conducted evaluations looking at the effectiveness of educational VR applications for learning disabled and autistic students. Its first work was with Makaton World. An early, informal pilot study found that most students were able to recognize and identify objects and hand signs. This study was followed by a more formal evaluation of the potential benefits of the application and its role in the school curriculum. Details on this later evaluation are not yet available.

The Life Skills World application, designed to promote self-directed activity in learning disabled students, is also the subject of continuing assessment. An initial evaluation examined how skills learned in a virtual supermarket transferred to a real supermarket [Cromby et al., 1996]. In the real shopping task, students were asked to find four items (identified by pictures on cards), put these items in their trolley, and take them to the checkout. Compared to their initial baseline performance, those students who received training in the virtual supermarket performed significantly better than the control group of students who had experienced different worlds from the Life Skills Worlds application. Students in the experimental group performed the task faster, and collected more correct items. The researchers note that it is possible that the advantage of the experimental group could have been caused by a greater familiarity with the shopping task, or the fact that the experiences with the Virtual Supermarket were more structured than those of the control group. To help resolve such uncertainty, the researchers are currently investigating changes in sub-skills such as memorizing items on the shopping list. They are also looking to develop measures for assessing generalized skills such as autonomy and decision making. Meanwhile, a second evaluation looking at the effectiveness of the Life Skills Worlds' Virtual House world for learning simple household tasks is ongoing. Evaluation of VIRART's AVATAR House is also ongoing.

Finally, an evaluation of Street World showed that autistic children could learn to perform simple tasks in a VE. This study demonstrated that students were able to master tasks of recognizing and identifying a moving car, and finding and walking towards a stop sign. Building on these positive results, these researchers are developing a second application, Object World, that will be used to investigate whether VR can be a useful medium for teaching autistic children to recognize classroom objects as compared to conventional teaching techniques.

4.1.1.3 Comparative Educational Effectiveness

Additional studies have compared the effectiveness of VR-based instruction with existing non-VR teaching practices. These studies have been on a smaller scale than those just discussed, but still provide useful evidence for the benefits of VR technology.

Researchers at Georgia Institute of Technology, GVU Center, used CDS to look at whether immersive VR aided the development of architectural design skills. CDS allows some architectural design activities to be accomplished from within the virtual world, for example, changing the color or texture of objects, and adjusting object orientation and position. Rather than progressing from 2D drawings to 3D models, it allows students to start with a type of 3D sketchpad. In an informal study, graduate students from the College of Architecture used CDS to complete a 10-week architectural design project. When compared with designs developed using paper or more traditional desktop design packages, the products of these students showed increased spatial understanding of architectural spaces. While the ability to make small design changes on-the-fly was valuable, it was difficult to make large changes. As a result, the researchers recommend combining traditional desktop modeling with an immersive option to allow the strengths of both environments to be exploited.

Researchers at James Cook University, School of Education, informally compared the effectiveness of navigating through a virtual world against the use of textbooks when learning about Egyptian pyramids. This study used a simplified version of the Great Pyramid virtual world included in the Virtus Archaeological Gallery. A small number of 7th grade students were given an introductory lesson on Ancient Egypt and shown some high quality pictures and diagrams of the pyramid. The students then explored the virtual Great Pyramid, identifying those aspects of the virtual world that they liked and making suggestions for improvements [Ainge 1996c]. Overall, the students stated their belief that the books were more successful for teaching them about the pyramid. While the students felt that the virtual world gave them a good feel for the size of the pyramid and the narrowness of the passageways, this particular world lacked detail and life-like texture. Problems in navigation and the unrestricted movement allowed by the absence of collision detection were often frustrating obstacles to explorations.

The evaluation of Zengo Sayu compared the use of a VR Japanese-based second-language learning approach with a similar approach using real-world objects, and with a traditional computer text-based approach. The key research questions being asked were: (1) Can students using Zengo Sayu learn some of the Japanese language? and (2) How does Zengo Sayu compare to other teaching methods in terms of language gains? All three treatments covered the same content (five colors, two nouns, two verbs, and five prepositions) and were designed to present instruction and offer rehearsal as consistently as possible. The main finding was that the instruction based in Japanese (both the Zengo Sayu and real-world treatments) gave a significant performance improvement over the English text-based instruction, and these two treatments themselves did not provide significantly different results [Rose and Billinghurst, 1996]. Thus indicating that, at least for Zengo Sayu, the VR-based instruction can be as effective as that provided by physical instructors.

Additional evaluations comparing VR-based instructional approaches with conventional classroom methods are underway at the University of Washington, HITL, using Phase World, and at North Carolina State University, using Object World.

4.1.1.4 Impact of Immersion

Cell Biology serves as another example of the effective use of formative evaluations and as an example of a study focusing on the impact of immersion and interactivity on effectiveness of VR-based instruction [Gay 1994]. The initial application was designed much like a textbook in that users first learned about cell requirements and cell functions before building a cell and testing its structure. In the first part of the evaluation, the researchers found that it took users a while to get used to the VR interface which distracted users from paying attention to the content. In addition, users were unable to remember the organelle function information that they needed to repair incorrectly structured cells. Consequently, Cell Biology was redesigned. One of the changes allowed users an opportunity to get acquainted with the interface before any learning began. Another change was to remove the reliance on remembering cell requirements by having organelles explain their function when selected and providing instant feedback on their correct usage. In the second part of the evaluation, researchers again used museum visitors to compare the impact of immersive, desktop, and video-tape viewing of the refined application. Overall, the interactive (immersive and desktop) users scored higher on post-testing of symbolic and graphic retention. But desktop users performed slightly better than the immersive users, although the researchers suggest that the differing resolution between the HMD used and monitor might account for this difference. However, immersive users did report more enjoyment, and more of these users stated that they would take a free biology class, as compared to users in the other two groups.

The ScienceSpace researchers compared the effectiveness of MaxwellWorld with that of a commercial 2D microworld called EM Field (EMF) [Salzman et al., 1997a, 1997b]. This commercial application is widely used and covers much of the same material as MaxwellWorld. The evaluation was performed in two stages focusing, respectively, on the impact of the different visualizations (2D versus 3D) and the use of multisensory cues. Lessons were designed to provide the same content and learning activities using each of the applications, focusing on concepts pertaining to the distribution of force and energy in electric fields. At the end of the first stage, both groups demonstrated significantly improved conceptual understanding, with MaxwellWorld students better able to define concepts than students who had used EMF. MaxwellWorld students showed comparable performance to EMF students in sketching concepts, performed better in demonstrating concepts in 3D, were better able to predict how changes to a source charge would affect the electric field, and could recognize symmetries in the field. In the second stage of the evaluation, a subset of the students was given an additional lesson in MaxwellWorld, this time supported by auditory and haptic cues. The results showed that students gained a significantly better understanding of concepts, and improved their ability to demonstrate these concepts in 2D and 3D representations. In particular, students who had previously experienced difficulty with the concepts found that the multisensory cues helped them to better understand the visual representations.

Overall, these results suggest that immersive 3D multisensory worlds can aid students in developing appropriate mental models better than 2D representations. The evaluation also provided insight into the nature of misconceptions that students hold. For example, the researchers found that after using MaxwellWorld or EMF, students were unclear how the electric field influenced charged objects and the relationship between potential and force. Future work will investigate whether the continuing misconceptions are remediated when the full power of the VR application is used, including multisensory representation and allowing a user to experience phenomena from the perspective of a test charge [Dede et al., 1996a].

The impact of immersion and interactivity on effectiveness has also been investigated by HITL researchers. Here an evaluation of an early version of the Atom World was conducted to look at the impact of these factors on student learning about atomic and molecular structure at the high school level [Byrne 1996]. Four treatments were used: high immersion and high interactivity (using Atom World), low immersion and high interactivity (a desktop chemistry world), and low immersion and low interactivity (using (1) a video recording of an Atom World session, and (2) a run-through of a session with the desktop chemistry world, both of these accompanied by supporting narrative). The obvious additional treatment of high immersion and low interactivity was not used because of the difficulty of eliminating interactivity from an immersion scenario and because of the expectation that such a VR scenario would be more likely to induce simulator sickness symptoms. The basic task that the students had to perform, or watch, was building two hydrogen and one oxygen atoms and combining these to form a water molecule. The major finding of this evaluation was that the groups of students who used Atom World and the desktop chemistry world both showed significant improvements between their pre-test and post-test scores, and these scores were not significantly different from each other. Thus, as in the Cell Biology evaluation, immersion did not have a significant impact on students' learning. The researchers suggest that lack of familiarity with the VR interface, as evidenced by the number of errors students made with the controls, a failure to fully exploit the potential of VR technology, and a low resolution HMD might have contributed to this finding. Again, as was found with Cell Biology, interaction was a positive factor, because the Atom World and Mac-based chemistry world groups outperformed students in the non-interactive treatments and students in a no-treatment control group.

An early study, conducted by researchers at Oregon State University, looking at the impact of perceived realism (immersion) on childrens' spatially related problem solving ability had similar findings. Again an immersive VR treatment was compared with a 2D, non-immersive desktop treatment. The results showed that immersion was not significantly related to spatially related problem-solving skills. These results were unexpected, and the researchers hypothesize they might be due to an insufficient number of experimental trials, difference in the number of trials for each treatment, and unreliability of one of the measures used [Merickel 1994]. It is likely that the rather different activities that students performed in each of the treatments also served to cloud the data.

These studies showed mixed findings for the impact of immersion on student learning. One study that examined the effects of immersion on one particular learning-related issue also raised interesting questions. In this case, researchers from James Cook University, School of Education, conducted a small study investigating the impact of immersion on recall [Ainge 1996a]. Here, the researchers assessed whether 6th grade students remembered more details from a simulated scene (the Room World) than from photographs of that scene. The results showed that VR did not help students recall which objects were in the room or object colors, although it significantly enhanced recall for the numbers of each type of object and the objects' locations.

4.1.2 Evaluation of Usability

4.1.2.1 General Usability

Several of the groups that have developed educational VR applications have paid special attention to issues of usability. Most have focused on the usability of specific worlds, although a couple have also addressed general issues pertaining to the usability of VR technology itself. Of course, one area where usability has been a critical issue is in evaluation of applications intended for use by physically or learning disabled students.

As mentioned in the previous section, the ScienceSpace worlds are being developed through a series of formative evaluations that have all considered usability. The recent evaluation of MaxwellWorld that compared the effectiveness of this application with EMF also considered usability. Students' ratings indicated that they found the various features of MaxwellWorld more difficult to use than those of EMF, but MaxwellWorld representations were easier to understand. However, neither of these differences were significant. Overall, students described MaxwellWorld as easy to use, interesting, and informative, and indicated that it was easier to remain attentive with MaxwellWorld than with the 2D counterpart [Salzman et al., 1997a].

One notable feature about the evaluations of the ScienceSpace worlds is that they have addressed the issue of multisensory and multimodal interfaces. One general finding is that multisensory (spatialized sound and haptic) cues can smooth interaction. The researchers suggest that these types of cues can prevent interaction errors through feedback cues and enhance the perceived ease of use. Multimodal (voice command, gesture, menu, virtual control, and physical control) interfaces can also ease interaction. The researchers found that multimodal interaction seems to enhance learning by offering participants the flexibility to adapt the interaction to suit their own preferences, and also facilitates distributing attention when performing activities in the virtual worlds. Overall, students have shown noticeable individual differences in their interaction styles, abilities to interact with a 3D world, and susceptibility to simulator sickness. The most recent evaluation of MaxwellWorld provides some specific data on the occurrence of simulator sickness symptoms, comparing student responses to MaxwellWorld and desktop EMF [Salzman 1997a]. While students who used MaxwellWorld did score significantly higher on a simulator sickness questionnaire for disorientation and oculamotor discomfort than those students who used EMF, there was no significant difference between the groups for symptoms of nausea. The overall simulator sickness score did not significantly predict learning outcomes.

While non-spatialized sound has been successfully used in several other applications, the evaluation of Virtual Gorilla Exhibit demonstrates that some care is needed in how non-spatialized sounds are used [Allison et al., 1996]. Virtual Gorilla Exhibit uses monaural audio presented to the participant, with additional sound feedback provided by a subwoofer concealed under the platform on which the participant stands. This audio is used to add realism and provide cues as to a gorilla's emotional state (contented, annoyed, or angry). In the prototype version of this application, the audio is played continuously at a constant volume, regardless of the participant's location with respect to the virtual gorillas. Students found that the constant volume confused them as to a gorilla's whereabouts. As a next step, the researchers plan to disable sounds when the sound source is a certain distance away from the participant, or when the participant is inside a building. Depending on the success of this approach, a spatialized sound interface may be incorporated in the application.

The usability evaluation of LAKE has also provided useful feedback to the application developers [Mikropoulos et al., 1997]. Subjects recommended introducing more visual realism into the virtual worlds, even at the expense of a slower frame rate, and the use of sound to further increase the realism. They also gave opinions on, for example, the use of virtual buttons and other means of navigation, and on the representations used to depict such things as diluted oxygen and phytoplankton. One surprising finding was that half the subjects stated that they experienced immersive feelings even though LAKE is a desktop application. Overall, the subjects, who were all future teachers, reported positive feelings for the use of VR technology in the classroom.

4.1.2.2 Usability for Physically and Learning-Disabled Students

The majority of work investigating usability issues for physically disabled students has been performed by Interface Technologies Corporation as part of the development of VESL. VESL is intended for use by students with cerebral palsy, multiple sclerosis, and muscular dystrophy, as well as by non-disabled students. The development of VESL began with a needs analysis that took account of the capabilities of students with a physical disability and guided the selection of hardware and software that was used [Nemire et al., 1994]. This was followed by an investigation where persons with cerebral palsy participated in an evaluation of the usability of a spatial tracking system (electromagnetic trackers placed on the back of the hand and forearm) that allowed manual interaction to be accomplished by students with minimal arm or finger control. Two different forms of predictive software were assessed for their ability to assist participants in "touching" a virtual target. Both forms increased participants' speed in touching the target and one also increased accuracy [Nemire 1995a]. The results of this evaluation were used to develop a refined set of prediction software that was then used in VESL. The prototype also supports speech commands.

A later formative evaluation of VESL itself examined a wider range of usability issues [Nemire 1995b]. Students (with and without disabilities), teachers, assistive device specialists, occupational therapists, and human factors engineers participated in this study. The questions asked pertained to the aesthetics of the virtual world (for example, the appeal of the colors and sounds used), usability (for example, the ease of navigation, enjoyability, and the utility of virtual controls), and immersion. Participants gave aesthetics an overall mean rating of 7.4 on a 9-point scale. The mean ratings for the different usability questions varied more than in other categories, ranging from 5 to 8 points, with an overall mean rating of 6.8. The participants seemed to experience a sense of presence, giving a mean rating of 7.2 for immersion.

The other developer of educational VR applications designed for use by both physically disabled and non-disabled students is Oregon Research Institute. Researchers here are currently conducting a pilot study intended to support the design of a controlled study investigating how well the Science Education World works for orthopedically impaired and regular students at the middle and secondary level compared to traditional non-VR science instruction.

Researchers at the University of North Carolina Medical School, North Carolina State University, Computer Science and Computer Engineering Departments, and TEACHC have investigated usability questions specifically related to autistic children. Using their Street World application, these researchers conducted an informal study to demonstrated that such children are able to tolerate an HMD and to navigate through a simple street scene by walking in the appropriate direction.

The VIRART researchers have examined the usability of particular input devices for severely learning-disabled students. The early Makaton pilot study showed that some learning-disabled students had difficulty in using a SpaceBall or mouse for world navigation. Subsequently, a number of population stereotype studies were conducted that looked more closely at the usability of particular navigation devices (SpaceBall and joystick) and interaction devices (mouse, glove, and touch screen) for severely learning-disabled students [Brown et al., 1995]. The researchers found that a joystick was the most appropriate navigation device in terms of facilitating control without leading to excessive levels of frustration, and a mouse or touchscreen was the most appropriate interaction device, depending on the level of disability.

4.1.2.3 Sense of Presence, Ease of Navigation, and Enjoyment

Information on student enjoyment of VR experiences, the sense of presence that students experienced, and their ease of navigating virtual worlds are provided from analysis of data collected in the VRRV program. Data was collected from nearly 3,000 students in grades 4 through 12. As reported by Winn [1995], all students indicated that they enjoyed their use of VR technology. However, the reported levels of enjoyment decreased with student age, and boys reported more enjoyment that girls. Findings on the feeling of presence experienced by the students were similar in that while high levels of presence were reported, these also decreased with age. Findings on the ease of navigation and interaction were less positive. Younger students had trouble using the wand device used to specify navigation commands, although these difficulties did decrease with age, as did ratings of disorientation when inside and leaving the virtual worlds. There were very few reports of other simulator sickness symptoms.

Additional findings on presence and navigation are provided by some of the efforts that have conducted evaluations of particular pre-developed VR applications. For example, students who used the Virtual Gorilla Exhibit seem to have experienced minimal presence. For example, although the researchers conducting the evaluation had expected participants to make physical gestures and approach the gorillas, many participants stayed in one spot and only occasionally turned to look or move towards something behind them. Those participants who did move through the virtual world acted as they would in the real world, choosing not to cross moats, run into rocks, or fly through the environment. On the other hand, some feelings of presence are implied by the participants' stated disappointment on the lack of haptic feedback that would allow them to touch the virtual gorillas.

The first formative evaluation of Safety World provided feedback on a number of usability concerns [Bell and Fogler, 1996]. When asked about HMDs, as opposed to desktop viewing, students rated the current benefits of HMDs as 3 or below, on a 5-point scale, but saw the potential of these devices as 4 to 5 points. The researchers found that the chief usability problem occurred in navigating around the virtual world. They noted the need to present information about joystick operation visually rather than textually. In general, the students did not read the provided text-based operating instructions, implying a general need for operating information to be made visually available in a virtual world. Another navigation issue was raised in the early formative evaluations of Vicher I [Bell and Fogler, 1995]. Many students had difficulty travelling through hallways and reported that this type of realism added little to the overall VR experience. Instead, teleports were the preferred method for navigating between rooms.

The informal evaluation of CDS investigated the success and problems with navigation and other interface techniques such as pull-down menus. The researchers reached the conclusion that virtual tools adopted from the desktop metaphor were well received and students found them easy to use.

4.2 Evaluations of Student-Development of Virtual Worlds

There are only a small number of evaluations to report on student development of virtual worlds. The majority of these have been conducted as part of efforts previously identified as research oriented. Only one evaluation has been identified where student development of worlds is an ongoing classroom activity. Details of the evaluations that have been conducted are given in Table 24.

Table 24. Completed Evaluations Using Student Development of Virtual Worlds

Performing Organization	VR World/Program	Purpose of Evaluation	Description	Major Findings
Evans Bay Elementary School	Virtual Museum	Effectiveness of VR as a research presentation medium	Informal study where one group worked with VR and the other group with paper.	- Students working with VR were more motivated, enjoyed and seemed challenged by this use of the technology. - Designing and problem-solving discussions were the most valuable outcome.
H.B. Sugg Elementary School	Virtual Pyramid	Educational effectiveness	Used pre-/post-testing to assess how examining a virtual pyramid from different perspectives and moving objects into it improved ability to compare, classify, and create pyramid models and understand their graphical manipulation.	- Students' ability to identify and draw correct perspectives of a pyramid improved.
James Cook University, School of Education	3D Shapes	Comparative educational effectiveness	Compared construction and exploration of 3D shapes worlds with construction and examination of 3D shapes built with card nets. Used pre/post-testing to assess impact on drawing shape appearances from different viewpoints, recognition of shapes in the environment, and writing shape names.	- VR significantly outperformed the card nets in ability to recognize shapes. - VR made no strong impact on shape visualization from different perspectives. - For all tasks, a greater percentage of VR students improved their scores than control (card net) students.
Kelly Walsh High School	Computer Programming Class	Comparative effectiveness for correcting science misconceptions	Formal study based on interviews and videotapes. Students from 2 high schools worked with students at 3 elementary schools. One group used VR, another did not use VR, but both followed a constructivist learning approach. A third group attended usual classroom activities.	- All three groups increased learning by roughly the same amount.
University of Washington, HITL	Pacific Science Center Summer Camp '91	Assess ability to work creatively with VR and enjoy that work	Pilot study based on opinion survey, video tape of student activities, and informal observations. Looked at student activities and social behavior during world building and world visiting, broad patterns of student response to VR, and at students' personal responses to their experiences.	- Students demonstrated the ability to use VR constructively to build expressions of their knowledge and imagination. - Students enjoyed the experience of VR. - Students accommodated quickly to orientation and navigation, and collaborated well.
	Pacific Science Center Summer Camp '92	Assess impact of gender, race, and scholarship status on ability to work creatively and enjoyably	Pilot study based on opinion survey and informal observations. Looked at impact of factors on issues such as sense of immersion, enjoyment of designing and building a virtual world, desire to build another world, desire to experience VR again, and enjoyment of the camp as a whole.	- Race and scholarship categories were highly correlated. - Gender was significant only on the sense of immersion experienced, with boys reporting a greater sense of immersion than girls. - Race/scholarship was significant only on reported enjoyment, with non-scholarship students reporting more favorable opinions about VR.

Table 24. Completed Evaluations Using Student Development of Virtual Worlds (continued)

Performing Organization	VR World/Program	Purpose of Evaluation	Description	Major Findings
University of Washington, HITL (Continued)	HIV/AIDS	Assess effectiveness of VR for "at risk" students, and assess VR's role within a curriculum	Informal study based on anecdotal and personal observation. Looked at how well students had learned about AIDS and computers (as evidenced by ability to construct HIV/AIDS world), their experience in visiting the world, and general motivation.	- Students showed higher motivation in attending class. - VR portion did not conflict with classroom balance and brought focus to topic studied.
	Puzzle World	To evaluate the impact of designing and experiencing virtual worlds as a spatial processing skill enhancement method	Used pre-/post-testing and interviews to assess ability in spatial relations, sequencing, classification, transformation and rotation, whole-to-part relationships, mental imagery, and creative problem-solving as evidenced by Inventory of Piaget's Developmental Tasks test.	- Although mean scores for each subtest did not vary significantly, the total mean scores did indicate significant improvement occurred. - Each subtest showed some improvement, with skills in classification showing the strongest improvement.
	Wetlands Ecology	Assess the effectiveness of developing wetlands ecology worlds to visiting pre-built worlds and traditional instruction	Used pre-/post-testing to assess factual recall and the ability to draw mental models of, say, the nitrogen cycle.	- Low-ability students who did world building significantly outperformed those studying in the traditional way. - High-ability students' performance was not affected.
	VRRV Entrée	Determine: (1) whether students learn from designing and building their own virtual worlds, (2) whether constructivist pedagogy with VR leads to different outcomes to traditional forms of instruction, and (3) student characteristics that affect how well they learned from world building.	Looked at impact of general ability, spatial ability (secondary school students only), and gender. Where possible, compared educational effectiveness of developing worlds with traditional methods for learning content Used exit questionnaire, pre-/post-testing, interviews, video tapes of student activities, and questionnaire assessing attitudes towards science and computers.	- Students who built virtual worlds did learn the content they were expected to. - Students who built virtual worlds did equally well, regardless of general ability. - Students who built virtual worlds had consistently better attitudes towards science and computers after experience. - Students learned more and enjoyed the project more who used 3D models to visualize their world before they built objects in the computer; were easily able to find the object they had made when visiting their world; and reported experiencing a high degree of presence. - Students who had difficulty navigating or who lacked a clear understanding of tasks to be performed in the world learned less and enjoyed the experience less. - At the elementary level, boys reported they had learned more about VR than girls and needed less time to build their worlds. At the secondary level, boys enjoyed the world building more than girls and spent more time on the computers. - High spatial ability was correlated with enjoyment, learning, and feeling of presence.

As shown in Table 25, the completed evaluations for this type of use of VR technology all focus on effectiveness. These evaluations are equally split between more formal experiments and informal studies. There have been no evaluations of usability and, in general, this issue is less relevant for most of this category of efforts.

Table 25. Types of Completed Effectiveness Evaluations

General educational effectiveness	Virtual Pyramid, HIV/AIDS
Effectiveness for Learning Disabled Students	Puzzle World
Comparative educational effectiveness	Virtual Museum, Computer Programming Class, 3D Shapes, Wetlands Ecology
Ability to work creatively/enjoy	Pacific Science Summer Camp '91
Characteristics that impact learning	Pacific Science Summer Camp '92, VRRV Entrée

4.2.1 General Educational Effectiveness

Only one formal study that focused on the effectiveness of student world building activities in isolation of other issues has been identified. In this case, teachers at H.B. Sugg Elementary School investigated whether world building could improve students' spatial skills. They found that having 5th grade students work in groups to build a virtual pyramid improved the students' abilities to identify and draw correct perspectives of a pyramid. In general, the greatest improvement was found for drawing the front view of a pyramid; from the total group of 19 students, the students who correctly drew the figure went from 3 in the pre-test to 13 in the post-test.

Researchers at the University of Washington, HITL have addressed the educational effectiveness of virtual world building activities for students in special populations. In collaboration with the Seattle Public Schools' Interagency, an informal study investigated whether building a virtual world helped the students classed as "at risk" learn about HIV/AIDS prevention, and improve their motivation and self-esteem. In this investigation, after receiving instruction on HIV/AIDS and on the software to be used, a class of students was tasked to developed a VR game about HIV/AIDS. After brainstorming a game concept, different groups of students developed different objects. Both the game concepts and the objects were then used by HITL researchers to create the actual game that the students could experience. The main findings of this study were that the VR portion of the curriculum worked well in the classroom setting, bringing focus to AIDS issues, and that students showed higher motivation in attending class [Byrne et al., 1994]. Substantial improvement in self-esteem was demonstrated by some students choosing to lecture about the project at other schools and volunteering to join a city-wide AIDS peer education project.

Finally, while the VESAMOTEX effort at Slaton High School has not included any structured evaluations of the effectiveness of student development of virtual worlds (and so is not included in Table 25), the teacher involved has compared grade scores for the students in physical science classes both before VR technology was introduced and afterwards. The students in these classes have a very diverse set of abilities, ranging from those classified as having special education needs to students identified as gifted and talented. These classes also include students with personal problems and difficulties such as drug abuse and teenage parenting. VR was first used in the spring of 1996. A comparison of grades at the end of this semester with those of the previous semester for over 70 students shows that more than 85% of the students increased their overall grade, in several cases by over 20%. These results are largely attributed to the increased motivation that VR technology seemed to generate in the students.

4.2.2 Effectiveness for Learning Disabled Students

As part of their work in investigating the effectiveness of VR technology for students in special populations, HITL researchers also have looked at the potential of virtual world building for helping neurologically impaired children develop 3D spatialization skills. The initial plan had been for the students to work together in choosing a virtual world to develop, but these students chose to work independently. While each child developed object pieces for the world he had conceived, the HITL researchers were still able to combine all these components in a single virtual world for viewing. This was a formal evaluation effort and, using the Inventory of Piaget's Developmental Tasks, the results showed that the intensive training in 3D thinking did significantly improve overall mean scores related to spatialization [Osberg 1993]. For five of the more difficult subtests, the students had pre-tested at below 6th grade level for three, and slightly above average for the other two. After the one-week course, the group had improved beyond the 6th grade level with some students showing abilities at the 8th garde level. The researchers note that the data does not indicate which aspect of the course did the most good, that is, whether or not it was the world development activities that led to the results.

4.2.3 Comparative Educational Effectiveness

Teachers at two schools have undertaken studies that compared the effectiveness of student world building activities with regular classroom practices. In the assessment of the value of VR as a research presentation medium at Evans Bay Elementary School, students were tasked to select a research topic and conduct research. The research information then had to be organized as if it were in a museum: using hall and alcove layout to show categorization and hierarchy of information, and using corridors and doors to reflect the links between the pieces of information. One group worked with paper and the other with VR. In comparing the work of the two groups, the VR group seemed more motivated, searching more widely for resources and utilizing computers in quite a sophisticated way. The VR group also engaged in more discussion and group cooperation.

At Kelly Walsh High School, participating students in a computer programming class each worked with two or three 6th graders at a local elementary school to develop virtual worlds. Students from chemistry classes in another high school worked with 6th graders from a different elementary school but did not use VR technology, while students at a third elementary school were taught a science unit following regular practices. Different topics were covered by each of the groups, though all addressed chemical and physical processes and changes at the atomic and molecular levels. All groups showed a small but significant increase in conceptual understanding by the end of the period of instruction. However, there were no significant differences in the knowledge gain displayed by the different groups [Moore and McClurg, 1995].

Two groups of researchers also have investigated the comparative effectiveness of this type of VR-based approach. Researchers at the James Cook University, School of Education, compared the development of 3D virtual shapes with the existing practice of building such shapes from cardboard cutouts on 6th and 7th graders' subsequent ability to identify these shapes [Ainge 1996b]. The subjects were drawn from two schools that have a majority of aboriginal students who are recognized as a disadvantaged group. Students were tested on visualizing the appearance of shapes from different viewpoints, recognizing shapes in the environment, and writing shape names. The shapes studied were the cube, rectangular prism, triangular prism, square-based pyramid, triangular-based pyramid, cone, cylinder, and sphere. Although VR had little impact on shape visualization, it was found to significantly enhance shape recognition and, on all tasks, a greater percentage of VR students improved their scores than did those students who built cardboard models. Another study by researchers at James Cook University is just starting. Here the researchers are interested in the comparative effectiveness of VR instruction in the area of learning about historical cultures. The work will include comparing traditional teaching methods with a VR approach and comparing the use of researcher-developed materials and student-developed materials. To this end, the types of materials that will be used will include historical pictures, a pre-developed virtual scene, student-developed virtual scenes, and student-build models (for example, cardboard models).

A study by University of Washington, HITL researchers conducted at Kellogg Middle School compared the effectiveness of a constructivist pedagogy that included student world development with traditional instructional practices. Although the HITL researchers had expected the VR treatment to be more effective than the non-VR treatment, there was no significant difference in learning between the two treatments [Osberg et al., 1997]. Four wetlands ecology cycles were studied across four classes. In each class, each student learned about one wetland ecology cycle using the constructivist/VR approach, two other cycles using a traditional classroom instructional approach, and had a no-instruction treatment for the fourth cycle (that is, instruction on some unrelated subject). The analysis was based on pre- and post-testing, and preparation of concept maps (both before and after the treatments) collected on the world they were assigned and a chosen world they wished to represent. Interview and survey information was also collected. The data provided no evidence that the constructivist approach, combined with world building, was more effective than the traditional instructional approach although, unlike the traditional approach, the constructivist approach did show a significant improvement over the no-instruction treatment. The researchers suggest that one reason for these unexpected results was that the students who participated were already experienced in the constructivist paradigm, although not world building, and this experience was applied even in the traditional instruction treatment. Nonetheless, the teachers involved in this project did feel that world building had some positive effects. For example, the students' language and presentation techniques evolved, they began to talk in terms of "perspectives" and "rotating the view," and seemed more willing to consider part-to-whole relationships. These changes were reflected in other classes and even personal relationships.

4.2.4 Ability To Work Creatively and Enjoyably

The University of Washington HITL's participation in the Pacific Science Center Summer Camps in 1991 was the first evaluation of educational use of VR technology reported in the public literature. During this summer camp, HITL researchers conducted a pilot study that focused on the ability of 10-15 year olds to use VR technology constructively to demonstrate certain knowledge or express their imaginations, and whether they enjoyed such work. More specifically, the researchers were interested in seeing what students were motivated to do given access to the technology and guidance in the world building process. The largely subjective results showed that, indeed, students could use this technology creatively and enjoyed their work. The researchers felt that students demonstrated rapid comprehension of needed concepts and skills, they were willing to focus significant effort toward developing their worlds, and that collaboration between students was very successful [Bricken 1992]. With respect to world construction, the students learned enough about the modeling software in 10-15 minutes to begin creating objects and later showed a fast accommodation to moving around in a virtual world and the nature of virtual objects. Object interaction was more difficult, perhaps due to the low resolution Virtual EyePhones HMD that was used. The students themselves showed great satisfaction with their accomplishments and consistently rated their appreciation of the technology extremely highly in an opinion survey. Even though low levels of disorientation were reported when experiencing the virtual worlds, the students reported that they felt that VR worlds were good learning environments as well as good places to play and work. As shown in Table 15, although still positive, student ratings on the world-building tools were less favorable. The unnatural nature of gesture-based interaction using a data glove also was a concern.

4.2.5 Student Characteristics That Impact Learning

The students at the Pacific Science Center Summer Camp in 1991 were predominantly computer-literate, male Caucasians who had access to a fairly expensive summer camp.

Table 26. Student Opinions About VR Technology During a Summer Camp (1991)[a]

VR Experience	
How did you feel about experiencing VR?	(1: did not enjoy - 7: enjoyed extremely 6.5
Do you want to experience VR again?	(1: not at all - 7: very much 6.8
Would you rather: go into a virtual world (1) see a virtual world on a computer screen (0)	(forced choice) .95
go into a virtual world (1) play a video game (0)	.98
go into a virtual world (1) watch T.V. (0)	.96
go into a virtual world (1) use your favorite computer program (0)	.98
World-building Tools	
	(1: did not enjoy - 7: enjoyed extremely
How did you feel about building Swivel worlds?	5.8
Do you want to learn more about building Swivel worlds?	5.7
Do you want to learn to program VR worlds?	5.6
Would you rather: build a Swivel world and go into it (1) go into a world that has already been built (0)	(forced choice) .76

a. Based on data in [Bricken 1992].

Consequently, the following summer, scholarships were provided to help students from other groups and backgrounds attend the camp. This allowed the HITL researchers to investigate whether factors of gender, race, or scholarship impacted students' interaction with and enjoyment of VR [Byrne 1993]. Since the researchers were also interested in looking at the use of VR in a curriculum-like setting, this time students were instructed to develop worlds with emotional themes. These students also reported positive VR experiences. With respect to gender, the only significant difference was found in response to a question on awareness of physical surroundings while immersed in a virtual world, with the boys reporting a greater sense of immersion. Race and scholarship categories were quite highly correlated, with significant differences being reported for questions about how much students enjoyed designing and building a virtual world, how much they would like to build another world, and how much they would like to be in a virtual world again. Although the ratings given by the scholarships students were less favorable than those of their colleagues, the lowest mean score for these students was 8.28 out of a possible 10, indicating that the scholarships students still ranked the VR experience highly.

Data collected during the VRRV Entrée program was also analyzed to look at the issue of gender. At the elementary level, self-reports on the amount of learning that took place indicated that boys benefited more that girls from world building activities. At the secondary level, boys reported more enjoyment from the use of VR technology than did girls. With respect to general abilities, the VRRV data indicated that students performed equally well. However, students with high spatial ability reported more enjoyment, learning, and a feeling of presence than did those with low spatial ability [Winn 1995].

4.3 EVALUATIONS OF MULTIUSER, DISTRIBUTED VIRTUAL WORLDS

As shown in Chapter 3, there have been few developments of multiuser, network-based educational VR applications. Consequently, there are only two evaluations to report: a completed evaluation for Virtual Physics and an ongoing evaluation for NICE. Details on the evaluation of Virtual Physics is given in Table 27. While these studies have looked at issues of educational effectiveness and usability, a significant focus has been on the role of collaboration in learning.

In the ongoing study with the research vehicle NICE, researchers are investigating interface, orientation, immersion and presence, motivation and engagement, as well as cognitive and conceptual learning issues. They are in the process of developing an evaluation framework that takes into account the measurement of both usability as well as conceptual learning attributes of the application. Because the VR medium is still new, these researchers have chosen to conduct their evaluations as a series of case studies using a small number of children rather than perform a formal evaluation with an entire class. The studies themselves follow a limited quantitative perspective and a highly qualitative approach. So far, children for the experiments have been selected on the basis of gender and their expertise in computer/video game playing. While only very preliminary and informal observations can be yet made, it seems that children who play video games need no instruction to begin using the VR application and feel more at ease when interacting with the virtual world. Indeed, all the children seem to gain the skills needed to the use the VR application quickly, but the ones inexperienced with video games are less animated in the virtual space. In terms of conceptual learning, initial observations reveal a high degree of diversity in how the children work with their small ecosystems, and in how they collaborate with each other or the virtual genies.

The goal behind the DEVRL project is to investigate the effectiveness of collaborative VEs for conceptual learning and developing skills in scientific problem solving. The Virtual Physics application developed to support this goal is itself designed to help students develop non-symbolic models of various physics concepts. The completed, informal experiment with this application evaluated both the level of physical knowledge that could be gained and types of participant interaction. The testing was performed using the Cannon, Bowls, and Friction worlds. Participants in the experiments were given a minimal introduction so that they would

Table 27. Completed Evaluations Using Distributed Virtual Worlds

Performing Organization	VR World/Program	Purpose of Evaluation	Description	Major Findings
University of Lancaster, Computing Department	Virtual Physics	Evaluation of (1) participant interaction, and (2) the level of physical knowledge that can be assimilated	Informal, subjective study based on videotapes and observations. Pairs of participants working simultaneously used the environment to perform tasks. After a familiarization session using the 3D Pivot world, subjects were assigned tasks in the Cannon, Bowls, and Friction worlds. Some students used an immersive interface and others a desktop graphical user interface.	- Role playing in collaboration can promote effective collaboration if the roles can be associated with appropriate cognitive processes. - During their collaboration, each pair of students tended to persist in a given role. - The immersive interface seemed the one most easily understood, providing better visual cues and a more intuitive interface. - The desktop interface presented navigation difficulties when users tried to track moving objects. - The worlds supported "reperception" of problems by allowing viewpoints to be varied and allowing a moving perspective that supported different frames of reference. - Most participants displayed little or no logical method, controls were rarely moved in isolation, and model building techniques appeared to be poorly developed.

be free to choose their own form of interaction. For example, using the Friction world, participants were shown the world, introduced to the method of moving balls over the table, and then asked to determine the function of two unlabeled controls. Most pairs of participants seemed to treat the tasks posed in the experiments as a simple game, using trial and error to solve the problems, rather than building an hypothesis about the system. Interestingly, the abstract nature of the Bowls world, and the posing of the problem as a friendly competition rather than a collaboration, presented the best results. While the approaches taken by the groups were very different, the solutions always resulted in the development of a model for the motion of a ball over a surface [Brna and Aspin, 1997].

With respect to the types of participant interaction that were evidenced, researchers found that most participants displayed little or no logical method and their conceptual model building techniques were poorly developed. Task solving activities invariably broke down into a dominant leader and passive follower mode of interaction, and the VR interface did little to mediate between different personality types. As a result of this experimentation, the researchers have defined three types of collaborative learning environments: task division, the game, and the mentor/pupil model. In the first case, a task that may normally be performed by one user is needlessly divided into a multiuser task, for example, one participant becomes little more than a camera for the other participant(s). The DEVRL researchers noted that there is a danger that all collaborative educational VR applications can degenerate to this. The second form of collaboration is the game, where they found that simple games, such as bowls, can present powerful learning devices for simple concepts, and the slightly competitive nature of a game can add to the collaboration. Finally, the mentor/pupil model is more suited to teaching complex material. While the mentor may be initially external to the virtual world, this role can be quickly assimilated into the participant group where it is passed between, or among, the participants as discoveries are made and passed on to other participants.

5. Conclusions

In the current transition from an industrial society to an information society, traditional instructional approaches based on the use of textbooks in classrooms have been called into question. Instead of memorizing facts, more emphasis is being placed on the higher-level thinking skills needed to construct and apply knowledge. Students must learn to locate, interpret, and creatively combine information, and to isolate, define, and solve problems. Additionally, education is no longer seen as something limited to a classroom or to a certain period in a person's life. Instead, education will be lifelong and must meet the needs of a flexible workforce.

This paper has reviewed some of the uses of VR technology that attempt to support these new visions. Before discussing any conclusions, it must be pointed out that VR technology, and its application to education, is still maturing. Moreover, almost exclusively, the studies have concerned one-time use of virtual worlds by any particular group of students, and there is no information on how students respond to the technology over the long term. Therefore, the conclusions given below present a snap-shot of the current state of affairs that will, hopefully, serve to guide further research on the optimal use of VR technology in education.

The remainder of this section returns to the questions raised in Section 1 to see what has been learned.

Questions relating to effectiveness of VR-based education:

- *Does learning in virtual worlds provide something valuable that is not otherwise available?* Unique capabilities of VR technology include allowing students to see the effect of changing physical laws, observe events at an atomic or planetary scale, visualize abstract concepts, and visit environments and interact with events that distance, time, or safety factors normally preclude. These capabilities allow virtual worlds to support a wide range of types of experiential learning and guided-inquiry that are otherwise unavailable. Other benefits include the ability to incorporate acknowledged good practices such as providing multiple representations and placing at least some instruction under the learner's control. While these latter attributes are not unique to VR technology, the technology does facilitate their use more than many traditional educational practices.

The work reported here provides initial findings that are suggestive of the value of these capabilities. The majority of uses of the technology have included aspects of constructivist learning and it is impossible to determine whether positive results are due to the use of this learning method, the use of a virtual world, or some combination of the two. However, this distinction is probably unimportant since, in the long term, the most significant impact of the technology is likely to be the support it provides for this constructivist learning.

• *How does the effectiveness of student use of pre-developed virtual worlds compare with traditional instruction practices?* Two formal evaluations have looked at the effectiveness of interacting with an immersive virtual world as compared with traditional learning activities. Both studies were in very different areas of curricula, with students of different ages and applications of varying levels of interaction and complexity. These studies also used different pedagogical approaches. The formal comparison of MaxwellWorld with a widely used roughly equivalent 2D computer application showed that the MaxwellWorld group did demonstrate superior learning in some areas and this advantage was retained after several months. The other formal evaluation found Zengo Sayu to be more effective in teaching Japanese than traditional computer-based instruction, and as effective as instruction provided by a human instructor.

The findings of one informal study were also positive, with students who used immersive VR developing a better understanding of architectural spaces that those who used paper or traditional CAD-based tools. Another informal study, this time with a non-immersive, simple walkthrough application, had less positive results. In this case, students reported that textbook instruction was more successful in teaching about pyramid structure than navigating through a virtual pyramid. This negative finding may have been influenced by the considerable difficulty students experienced in navigating through the narrow and sloping passageways inside the virtual pyramid.

These types of evaluations can support decisions as to whether a particular application warrants further development or introduction into practical use. As yet, however, researchers have not tried to identify specific characteristics that make one form of instruction more effective than another. There is a need for a series of evaluations that control the variables in question to try and pin down such characteristics. This type of information would provide guidance as to when a particular type of VR application should be considered and then help to guide the development of the application to ensure its effectiveness.

• *How does the effectiveness of student development of virtual worlds compare with other instructional practices?* The three studies that have addressed this question were, again, conducted in very different areas of curricula, with students in different age groups, and used different hardware and software development platforms. The Wetlands Ecology effort where some students developed immersive virtual worlds did find a significant advantage for low-ability students but there was no significant difference in the knowledge gain for high-ability students. The HITL researchers who conducted the Wetlands Ecology effort note two factors that could have contributed to the lack of a significant advantage for some students who used VR technology. First, there was considerable overlap of concepts among the different wetlands cycles studied and, secondly, all the students who participated in the Wetlands Ecology effort were already familiar with constructivist learning practices. The Computer Programming Class effort reported a similar finding for lack of a significance in the learning between the students who developed immersive virtual worlds and those participating in regular classroom activities. In this case, however, the several groups of students involved in the effort were free to address different topics within a defined area of the science curriculum and this makes interpretation of this finding difficult. The study at James Cook University was more controlled. Here researchers compared the value of creating non-immersive virtual worlds that contained 3D shapes with the construction of card net shapes. This study had positive results with respect to student recognition of the shapes but failed to show any strong advantage of the use of VR technology for helping students to visualize shapes from different perspectives. While simple, this use of the technology seems highly appropriate and the mixed results are surprising. It would be interesting to see whether use of immersive VR technology would lead to similar findings.

No conclusion on the effectiveness of student world development activities, compared with traditional classroom practices, can be made based on the mixed results of these particular studies. Many additional studies are required to isolate the impact of factors such as pedagogy, curriculum, and the method of student development of worlds and determine when and how student development of virtual worlds should form part of classroom activities.

- *How does the effectiveness of student use of pre-developed virtual worlds compare with that of student development of virtual worlds?* The only evaluation that has addressed this question is the Wetlands Ecology study performed by the University of Washington HITL. In this effort, each group of students not only developed an immersive virtual world depicting one wetland cycle and received more traditional classroom instruction for a second cycle, they also visited the virtual world for a different wetlands cycle developed by another group. As before, no significant differences in the knowledge gained were found when students visited a predeveloped virtual world as compared with developing their own world. Again, the overlap in concepts among the different cycles could have contributed to this finding. Note, moreover, that all "predeveloped" virtual worlds used in this evaluation were themselves developed by students and had no significant pedagogical component.

In general, it may not be appropriate to compare the learning effect of working with pre-developed applications and student development of virtual worlds because some curricula elements may benefit by one type of use and some by the other. The teachers and researchers who have led efforts where students developed virtual worlds as part of their learning activities believe that learning primarily occurs as a consequence of the research, world design, and world construction activities rather than experiencing the usually quite simple developed worlds. On the other hand, pre-developed applications typically address more complex subjects and provide the student with quite sophisticated methods of guided-inquiry for knowledge construction. Already the current sets of pre-developed applications and world building efforts are starting to show fairly consistent patterns of usage. Pre-developed applications are typically used for those circumstances where students must manipulate the virtual environment and perform experiments in order to learn basic and complex concepts. Whereas the goal underlying student development of virtual worlds is for students to demonstrate knowledge they have acquired.

- *How do the effectiveness of immersive and non-immersive virtual worlds compare?* Several groups have compared the effectiveness of immersive VR with non-immersive approaches. Often these assessments have used 2D computer worlds or simulations that are quite different than the immersive application. For example, CDS and Spatial Relations World were both compared against the use of computer-aided design (CAD) packages (in both, positive findings for immersion were found). Only three studies that compared immersive and non-immersive viewing of the same, or similar, virtual worlds were identified. Two of these studies used the Cell Biology and Atom World applications and found that the important factor for performance was interactivity, not immersion. Although in the case of Cell Biology, the researchers did find the immersive VR performed best for symbolic retention, non-immersive VR was better for function retention. The third study compared immersive MaxwellWorld with an equivalent 2D computer simulation that provides similar levels of interaction. Here, while each group of students performed similarly in most cases, some benefits for the 3D viewing supported by immersion were found. In particular, the students in the immersive condition were better at describing the 3D nature of electric fields.

While the evaluations show uncertain learning benefits for immersion, it is important to note that the participants in the immersive conditions in these studies expressed more enjoyment and motivation to learn than those in the non-immersive conditions.

- *How well does VR technology support collaborative learning between students? Is this collaboration educationally effective?* Some researchers suggest that collaborative learning can be achieved by having two or more students work together with "single-user" pre-developed applications by taking turns to guide the interaction, record observations, or experience the virtual world. However, there are no reports on how successful this approach is in practice. On the other hand, the majority of student-development of virtual worlds has taken place with students working in groups. In these cases, the teachers or researchers involved have observed greater levels of meaningful discussion between the students though there is no data on whether such collaboration impacted educational objectives.

Multi-user, distributed applications are specifically intended to support collaborative activities within virtual worlds. Of the three such applications for which details are available, Network Racer has well defined roles for each participant and participants appear to have had no difficulty in using these roles to guide their collaboration. The interactions between students in NICE are primarily of a social nature and, as yet, the researchers have drawn no conclusions about the effectiveness of this interaction. The informal evaluation of Virtual Physics does provide some interesting points, notably that role playing can support collaborative learning if the roles can be associated with appropriate cognitive processes, otherwise there is a tendency for collaboration to degenerate into a basic follower-leader paradigm.

The potential of VR technology to support collaborative learning seems very high, but there is a lack of knowledge on how to exploit the technology to actually support this type of learning. This shortcoming is not a reflection on the technology itself because little is known about collaborative learning. Once the characteristics and benefits of different types of collaboration are better understood, then it will be possible to assess the advantages that VR technology might bring to bear. Of course, collaborative VR applications may themselves prove useful tools for conducting such research.

- *Is VR-supported learning cost-effective?* It is too early to attempt to answer this question. As this paper has shown, there is some data on educational effectiveness, but it is sparse and case specific. Data on the financial costs of developing VR applications is not publicly available and there is a lack of data on related costs, such as maintaining VR equipment.

Questions concerning where VR technology should and, equally important, should not be used (considering both educational content and student characteristics):

- *For what type of educational objectives or material is VR technology best suited? Where is it not suited?* It is easy to say that VR technology is suited for those situations where students can be guided in the construction of knowledge or where they need to learn concepts that are highly visual in nature, and that it is not suited for predominantly text-based materials. Such general statements, however, are insufficient to select and guide appropriate uses of the technology. The technology already has been used for a wide variety of educational subjects and these applications provide some indications of where it is suited. However, there is very little data as to what characteristics of the technology support particular types of instruction. For example, why did building a set of basic 3D geometric shapes help students to recognize those shapes but did not help them to visualize and draw the shapes? Or why did students receiving auditory and haptic cues, in addition to visual cues, perform better on questions relating to velocity and acceleration, but worse on predicting system behavior? Answers to these types of questions are needed to determine the strengths and weaknesses of the technology and those situations that are most apt to benefit from its use.

- *Are there specific student characteristics that indicate whether VR-based education is appropriate? Does the technology benefit only certain categories of students?* It has been proposed that VR-based instruction will particularly benefit those students who are visually based. This is very likely, but there is no hard evidence that such is the case. The evaluation of the Wetlands Ecology effort suggested that less-gifted students and those starting with less subject-related knowledge benefit most from use of the technology. However, analysis of the subjective data collected from the many students who participated in the VRRV Entrée program indicated that students performed equally well, regardless of general ability. This data also indicated that students with high spatial ability performed better and enjoyed the use of VR technology more than those with a low spatial ability. It must be noted, however, that all this data was collected during student world development activities, and equivalent data is not available for instances where students have used pre-developed VR applications.

VRRV data also indicates a worrisome influence of gender, in that boys at the elementary level reported higher levels of educational effectiveness and took less time to build virtual worlds than did girls. At the secondary level, boys reported more enjoyment of world building levels. Also, in the VR program at the Pacific Science Center Summer Camp in 1992, boys reported experiencing a greater sense of immersion than did girls.

Additional research must be performed to take a closer look at the possible influence of gender and other student characteristics on the effectiveness of different types of educational uses of VR technology. For example, do boys typically have a greater experience with using computers or playing video games which gives them some advantage for using VR technology? It may be that different groups of students require different types of introduction to the technology or prior training in skills such as spatial awareness. Investigation of these issues is not only needed to ensure effective use of VR technology, but also its equitable use.

With respect to the potential educational effectiveness of VR technology for learning-disabled students, two formal studies by the VIRART group have shown that the use of pre-developed VR applications can help in teaching a special communication language and everyday life skills. A study by the TEACHC group showed that such applications can also help autistic children learn to recognize objects. HITL researchers demonstrated that world building can help to develop spatial skills in neurologically-impaired students. There results are encouraging. However, as shown by the 3D Letter World effort, interacting with most virtual worlds does require some minimum level of hand-eye coordination and spatial awareness skills that some special needs students may lack.

Questions concerning potential student and teacher acceptance of VR learning environments:

- *Do students find VR interfaces easy to work with?* Overall, students' reports on usability indicate that navigating through virtual worlds is one of the major problems confronting the use of VR technology. Because navigation is a fundamental activity in virtual worlds, this is a crucial area of concern. It seems unlikely that anything in advance of the current set of devices and metaphors can be done to improve navigation in non-immersive virtual worlds, although there is scope for improvement in immersive virtual worlds. The difficulty with navigation is, however, an indicator of a larger problem. That is, that the current interaction paradigms of command lines and graphical user interfaces used for interacting with a 2D space are insufficient to cover the wide range of interactions required with virtual worlds. In the absence of a general 3D interaction paradigm there is little commonality between VR application interfaces and the variety of types of input devices being used leads to additional differences in how interaction commands are given.

There is some evidence about the types of VR interfaces that students prefer. Several evaluations have demonstrated that students like multimodal interfaces, though some modalities are preferred over others. For example, in the few cases where gestures were used to control the interaction with the virtual world, students reported that they liked this type of interaction less than others (such as menu-based interaction). Evaluations of NewtonWorld and MaxwellWorld showed that students liked the use of multisensory interfaces and that the use of auditory and haptic feedback can aid in learning. Yet multisensory learning is an area where little is known and research is needed to ensure appropriate and effective use of different types of sensory feedback. Perhaps the most important conclusion that can be reached from the studies reported here is that students vary widely in their interaction styles and in their ability to interact with a virtual world.

The low resolution of current display devices means that text does not fare well in virtual worlds and the usual workaround is to take over most of the display to present needed text, at the expense of displaying the virtual world itself. While most applications need to include some text to present information, speech technologies could be used to minimize the reliance on text for interaction. Unfortunately, the use of voice communications has been minimal so far. More research into how to accommodate voice interaction in a virtual world is needed. This is particularly critical for multi-user applications.

The usability of HMDs is a topic of wide concern. Though little data on this issue was collected in the evaluations reported here, there are some noteworthy points to make. First of all, few students commented on the limited resolution provided by most current HMDs. The problems that were reported concerned difficulties with focusing the display. HMDs were used for extended periods, although some students reported eyestrain after 90 minutes of use. The weight and cumbersome nature of HMDs were not mentioned, and even autistic children were able to use this type of display.

Another important issue relating to immersive applications is simulator sickness. Here, gain, little data has been collected. Only one evaluation specifically looked at this question and in this case users of MaxwellWorld did report more occurrences of disorientation and ocular discomfort than students using a non-immersive 2D counterpart, although there was no significant difference in reports of nausea. Overall simulator sickness scores did not predict learning outcomes. In addition to this single study, other researchers have noted that the occurrence of nausea is rare, and the most common symptom of simulator sickness is disorientation. More data on the frequency and severity of such symptoms is needed.

There has been some commendable work looking at the usability of VR interfaces by students with physical disabilities and learning disabilities. This type of research is to be encouraged. One of the goals should be developing a set of interface and experiential characteristics that need to be supported for different groups of learners, along with guidelines for building such characteristics into educational VR applications.

- *Does the effective use of VR technology change the teacher's role in the classroom?* The HITL researchers have worked with a larger number of teachers than any other single group. These researchers report that teachers found that, whether they used pre-developed applications or had students develop their own virtual worlds, their roles in the classroom changed. Instead of being a teacher with all the answers, they became facilitators who supported students in their discovery of worlds and building ideas based on information gained from those worlds. This change in the teacher's role is one of the ways in which VR technology has long been expected to influence current educational practices and points out the need to prepare teachers for these new types of activities. East Carolina University offers a course for education students in how to develop and use VR applications. Also a few developers of pre-developed applications provide some teacher training for their specific applications. But wider questions as to how teachers should be prepared for this new role, and what different types of resources they need, remain to be investigated.

There are additional issues to consider for immersive "single-user" VR applications. The fact that it is difficult for teachers to monitor students' moment-by-moment activities can present challenges for lesson administration. Also, current applications do not provide teachers with assistance for assessing a student's learning or recognizing particular problems a student may have with the material. The integration of intelligent tutors into educational VR applications seems a logical next step that should help to resolve some of these problems. Indeed, given the sophistication of some current VR applications, it is surprising that no evidence of such integration was found. (A couple of applications do include intelligent guides, but none of these maintain models of student knowledge that can be used to guide further instruction or provide teacher feedback.)

- *What are student and teacher reactions to the use of this technology?* Based on data collected from thousands of students of different ages, using different applications with differing interfaces, there is overwhelming evidence that students enjoy both experiencing pre-developed applications and developing their own virtual worlds. Use of VR technology seems to serve as a valuable motivating factor. For example, in the VESAMOTEX project, the introduction of VR to the classroom improved attendance and reduced the number of negative progress reports that had to be sent to students' parents. Even more telling, several "at risk" students who participated in a HITL effort where they developed a virtual world designed to increase awareness of HIV/AIDS prevention, subsequently volunteered to become involved in activities to educate their peers about the danger of the HIV/AIDS virus. Does this enjoyment and increased motivation last? There is no data to answer this question, although the ScienceSpace researchers, who have had students use an application up to three times, feel that learner motivation will remain high, even when the novelty factor of VR technology has worn off.

The single teacher who appears to have the most experience with the use of VR technology in the classroom is at Evans Bay Intermediate School where students have been very active in the development of virtual worlds. This teacher points out that he is not a trained researcher and he is working out his own methodology for optimum use of the technology through trial and error. His impressions so far are that: (1) 3D spatial relationship concepts are rapidly accelerated, (2) higher-level thinking can be stimulated if the tasks assigned to students are challenging and of a problem-solving nature, and (3) again, motivation for many students is extremely high. There are no reports of teachers who, having tried the technology in their classrooms, decided not to use it. The largest problem seems to be a lack of resources that limit how the technology is used.

Two surveys designed to aid in defining VR's role in education also provide some input on teachers' reactions to the technology. While the first of these surveys focused on the use of VR technology in environmental education [Taylor 1994] and the second looked more broadly at K-12 education [Yu 1996], these surveys asked similar questions. In both cases, a majority of respondents (over 200 for each survey) said that they would use VR technology if it were affordable, available, and easy to use for students and teachers. When asked what type of research they thought was necessary, respondents first of all recommended that educators and VR developers should work closely together in developing educational programs, and suggested areas of research including: studying the advantages for learning from a VR representation as compared to learning from a 2D representation, studying what constitutes an effective virtual learning environment, and creating standards for both building and measuring the effectiveness of educational VR applications. Areas perceived as most beneficial were the ability for students to experience situations that were not accessible in the real world (including changes in scaling and/or time), programmable participation, and enhancing the education of students with disabilities. It is encouraging to see that work in most of these recommended areas is underway. For example, the development of the MAEL program and several VR applications have been guided by teacher input, and Global Change, the ScienceSpace Worlds, and Atom World are just a few of the applications that allow students to experience situations that are otherwise inaccessible. However, as previously mentioned, work has yet to start in trying to characterize what constitutes an effective learning environment and, at this time, it seems premature to start developing standards for building and measuring the effectiveness of educational VE applications.

Practical questions:

- *Are the hardware platforms and minimum set of interface devices required affordable to most schools?* Virtually any PC can be used for the development or desktop viewing of non-immersive virtual worlds. Consequently, this basic level of technology should be within the reach of most school budgets. If 3D viewing of non-immersive virtual worlds is desired, then additional graphics processing power and special interface devices such as shutter glasses or 3D projectors and passive glasses are required and these can incur significant additional costs.

The basic level of technology required for immersive virtual worlds is more expensive. Here the lowest-end hardware platform that can be reasonably used is a Pentium-level PC augmented by special graphic accelerator boards. The least expensive immersive visual display is an HMD and the price of this type of device starts at just under $1,000. Additional special interface devices, such as a head tracking system and six degrees-of-freedom mouse, are usually required. Together, this equipment puts the current price of an entry-level immersive VR hardware platform at around $10,000. A more realistic figure for a system suitable for practical, every-day use and capable of supporting timely interaction with complex worlds is in excess of $25,000. Note, moreover, that these are figures for a single platform and efficient classroom use of the technology usually requires several platforms. This expense is beyond most elementary, middle, and high school budgets. Some of the costs will decrease as the technology itself and its market matures. But since technology research and development is still required in many areas, major cost reductions will be slow in coming.

- *Are the needed software development tools available?* A wide range of VR software development packages are available at a range of costs. The more powerful ones can require training to use effectively and can cost several thousand dollars; these packages are best suited for professional world developers. There are half a dozen or so simple, inexpensive development packages suitable for use by students, primarily for the development of non-immersive virtual worlds. (Some studies looking at the comparative ease of use of three such packages are underway.) But there is a shortage of mid-range products that provide a comprehensive set of easy-to-use tools for developing immersive applications at a reasonable cost. In the interim, several researchers are using their own custom-build tools or tools not specifically designed to support the development of virtual worlds, for example, various CAD and other modeling packages.

In this area, the development of VRML is a factor to watch. Already most development packages provide support for VRML and VRML is starting to be used to distribute virtual worlds over the web. At least one VRML-based development package has been brought onto the market, although this event is too recent to allow any estimates on how widely used this product may become. The current version of VRML is still very limited in many important ways but the language has considerable support in the VR community.

- *Is the technology currently mature enough for practical use?* By and large, the technology needed for non-immersive virtual worlds is mature and becomingly widely used in many different application areas. The major outstanding problem is the difficulty experienced in navigating around a virtual world and the best solution is most likely not technological but practice to develop needed skills.

With respect to immersive virtual worlds, the fact that the technology is already is limited practical use in a variety of application areas does not necessarily demonstrate its maturity. Current uses of immersive VR technology tend to be isolated examples of what proponents of the technology can achieve. There are several technological problems that stand in the way of widespread use of the technology. Affordable, higher resolution immersive displays are needed and, in the case of HMDs, wider fields of view and more comfortable devices. Delays in scene updates and tracker inaccuracies can also be problems when head-tracking is used. New metaphors that facilitate interacting with immersive virtual worlds and, in particular, that support multimodal and multisensory interfaces are required. Likewise, advances in integrating VR technology with networking technologies are needed to support collaborative immersive virtual worlds. While there is ongoing research in all these areas, the advances required to achieve the level of technology maturity needed for widespread, practical use of educational immersive virtual worlds is unlikely to occur within the next five years. Less urgent, but also desirable, is the development of affordable spatialized sound displays that could increase the realism of virtual worlds. Inexpensive haptic feedback vests have already demonstrated their usefulness in the ScienceSpace applications, but there is a lack of affordable, general-purpose high-resolution haptic feedback devices. Here technology development is proceeding at a slower pace.

Purchasing special VR-related devices and acquiring continued support for them are additional areas of concern. Until very recently, the developers of these devices have tended to be small companies who were competing for a small amount of business. This led to an unstable marketplace where several companies have closed or changed their area of business over the last several years. This situation seems to be changing as more buy-outs and consolidations between organizations are taking place and these changes should result in greater market stability. Nonetheless, few VR interfaces devices provide a high level of robustness and the potential for reliable customer support must be considered during product acquisition.

A final issue concerns the integration of VR technology and the Web. Already there are several browsers on the web that can be used for non-immersive viewing of virtual worlds, although these browsers only support very minimal interaction with the worlds. However, the ultimate goal here is to allow students to collaborate in educational activities using an immersive virtual world, regardless of their geographical location. While several groups are planning to conduct research in this area, there is no progress to report as yet. Meanwhile, studies looking at the bandwidth and connection requirements for collaborative systems that support immersive viewing with voice, sound, and additional modalities (such as haptic feedback) are needed to determine how well the evolving Web is likely to support projected VR technology capabilities.

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List of Acronyms

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AAAS	American Association for the Advancement of Science
AIDS	Acquired Immune Deficiency Syndrome
BTEC	Business Technician Education Council
CAD	Computer-Aided Design
CAVE	Cave Automatic Virtual Environment
CD	Compact Disc
CDS	Conceptual Design Space
DEVRL	Distributed Extensible Virtual Reality Laboratory
DIVE	Distributed Interactive Virtual Environment
DOF	Degrees of Freedom
EMF	EM Field
GULLIVR	Graphical User Learning Landscapes in Virtual Reality
GVU	Graphics Visualization and Usability
HCC	Haywood Community College
HITL	Human Interface Technology Laboratory
HIV	Human Immune Virus
HMD	Head-Mounted Display
HP	Hewlett-Packard
I/O	Input/Output
IEC	International Electrotechnical Committee
ISO	International Organization for Standardization
JSC	Johnson Space Center
LAKE	virtuaL Approach to the Kernel of Eutrophication
LIVE	Learning in Virtual Environments
M.A.	Master of Arts

MAED	Master of Arts in Education
MAEL	Mobile Aeronautics Education Laboratory
MOO	Multi-User Domain or Dungeon (MUD) Object-Oriented
MUD	Multi-User Domain or Dungeon
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NCSA	National Center for Supercomputing Applications
NCREL	North Central Region Educational Laboratory
NICE	Narrative, Immersive, Constructionist/Collaborative Environments for Learning in Virtual Reality
NRC	National Research Council
NSF	National Science Foundation
PC	Personal Computer
RSE	Resource for Science Education
SEMAA	Science, Engineering, Math, and Aerospace Academy
SGI	Silicon Graphics, Inc.
TBD	To Be Determined
TCP/IP	Transmission Control Protocol/Internet Protocol
TEACHC	Treatment and Education of Autistic and Other Communications Handicapped Children
TRI	Transition Research Institute
TPR	Total Physical Response
UK	United Kingdom
VESAMOTEX	Virtual Education - Science and Math of Texas
VE	Virtual Environment
VESL	Virtual Environment Science Laboratory
VIRART	Virtual Reality Applications Research Team
VR	Virtual Reality
VRDS	Virtual Reality Development System
VREL	Virtual Reality and Education Laboratory
VRML	Virtual Reality Modeling Language
VRRV	Virtual Reality Roving Vehicle

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13. ABSTRACT *(Maximum 180 words)*

The potential of VR technology for supporting education is widely recognized. It has already seen practical use in an estimated 20 or more public schools and colleges, and many more have been involved in evaluation or research efforts. This document reviews current efforts that are developing, evaluating, or using VR technology in education. It builds a picture of the states of the art and practice, and reviews some of the critical questions that are being addressed. Educational uses of the technology are broadly distinguished as those where students interact with pre-developed VR applications and those where students develop their own virtual worlds in the course of researching, understanding, and demonstrating their grasp of some subject matter. Forty-three efforts in the category of pre-developed applications and another 21 efforts in the category of student virtual world development are reported in this paper. The results of 35 evaluations that have been completed on these efforts are summarized. Another 20 ongoing or planned evaluations are identified.

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