Summer Students in Virtual Reality: A Pilot Study on Educational Applications of Virtual Reality Technology[1]

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INTRODUCTION

Virtual Reality (VR) is a new way to use computers. VR eliminates the traditional separation between user and machine, providing more direct and intuitive interaction with information. By wearing a head-mounted audio-visual display, position and orientation sensors, and tactile interface devices, we can actively inhabit an inclusive computer-generated environment. We can create virtual worlds and step inside to see, hear, touch and modify them.

Now that computing power has increased to meet the demands of real-time processing, VR technology has entered a period of public attention and wide industrial interest. Major corporations and companies worldwide are actively exploring the use of this technology for a variety of application areas, including telecommunications, arcade and home entertainment, production and assembly management, health care, digital design, and product sales and marketing.

A growing number of universities and research laboratories are doing the work necessary to develop more sophisticated VR systems. The production of cost-effective VR components is underway in America, Europe and Japan. It is expected that within the next five years, a variety of affordable high-performance personal computers and workstations with networked VR capabilities will be on the market.

In anticipation of the widespread availability of this technology, this goal of this study is to take a first step in evaluating the potential of VR as a learning environment. We gathered two reciprocal kinds of information during the seven week process. The primary focus was to evaluate VR's usefulness and appeal to students ages 10 - 15 years, documenting their behavior and soliciting their opinions as they used VR to construct and explore their own virtual worlds. Concurrently, we used this opportunity to collect usability data that might point out system design issues particular to tailoring VR technology for learning applications.

This report will outline the theoretical framework of the study, describe the research context and outline the students' VR activities. Both the pedagogical methodology in designing the students' learning experience and the observation methodology used to record and evaluate student responses are described. The discussion of these observations is followed by descriptions of the virtual worlds constructed by students. The report concludes with a preliminary evaluation of the usefulness of VR for education.

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THEORETICAL FRAMEWORK

What we now call Virtual Reality has existed in various forms for three decades, and has already proved to be a useful learning environment for adults. The first head-mounted display was successfully devised to enable people to understand and manipulate computer-generated information more easily [Sutherland 1963]. VR has been developed over the past 20 years to facilitate learning and performance in high-workload environments in the U.S. Air Force [Furness 1978]. Flight simulators, which combine physical and computer-generated elements to create task-specific learning environments, have been highly effective in pilot training. Current VR systems provide new capabilities for perceptual expansion, for creative construction and for unique social interactivity [Bricken 1991a].

These characteristics of VR are relevant in three areas of educational theory: experiential education, constructivism, and social learning.

The experiential quality of VR provides a capability that is fundamental to the learning process [Dewey 1916, Brunner 1962, Silberman 1970, Papert 1980]. A virtual world is a *place* where participants can have any number of different learning experiences. By including them within these three-dimensional multi-sensory environments, and closely coupling their natural behaviors to system functionality, participants feel a strong sense of *presence* [Zeltzer 1990]. Interacting in VR involves "purposeful movement that coordinates the cognitive, the psychomotor, and the affective domains" [Harrow 1972], engaging the whole learner in the task at hand.

Children actively build their own categories of thought about the world [Piaget 1929], and encouraging students to construct their own knowledge is demonstrably effective in learning [Duffy & Jonassen: in press, Jonassen 1991, Spiro & Jehng, 1990]. Virtual worlds are constructive environments in which participants can create, manipulate and edit any form of digital information. Objects, processes and programmed inhabitants of the virtual world are elements for active problem solving. "In many instructional settings, students acquire only facts rather than acquire tools for problem solving. They often have not experienced the kinds of problems that make information relevant and useful, so they do not understand the value of this information." [Bransford 1990]

"Human learning presupposes a specific social nature and social process" [Vygotsky 1978]. Virtual worlds can be networked to provide shared environments that allow wide-bandwidth communication and collaboration between local or distant participants. The ability to *literally* exchange or share points of view in multiple-participant virtual worlds may intensify this social learning experience [Brown 1988]. Co-creating virtual worlds for learning allows teachers and students to use computers in a cooperative group situation, where learners tend to be more productive [Belkin 1977].

RESEARCH CONTEXT

The Technology Academy is a technology-oriented summer day-camp, offered by the Pacific Science Center to students from ages 5 - 18. The Academy offers seven camp sessions, each a week long. Student activities center around hands-on exploration of new technology. Academy "student researchers" are given a choice of focus areas such as robotics, MIDI digital sound interfaces and multi-media. In the summer of 1991, in cooperation with HITL researchers and sponsors, students were first given the option to explore the area of VR.

The VR student research groups were limited to approximately 10 new students each week, ages 10 years and older. A total of 59 students from ages 10 - 15 self-selected for participation over the seven week period. The average age of the students was 13 years, and the gender distribution was predominantly male (72 %). The students were of relatively homogeneous ethnic origin; the majority were Caucasians, along with a few Asian Americans and African Americans. The group demonstrated familiarity with Macintosh computers, but none of the students had worked with 3-D graphics, or had heard of VR before coming to the Technology Academy.

One Technology Academy teacher and one teaching intern shared primary responsibility for the VR student researchers, along with support from other Academy teachers and Science Center staff members.

HITL scientists provided pre-session and ongoing training to Technology Academy teachers, which included experiencing VR using the laboratory's collection of virtual worlds. Teaching materials provided by HITL included videotapes describing the technology with examples of virtual worlds developed by HITL, NASA, VPL Research, Inc., and the University of North Carolina. Teachers also received written virtual world design and modelling guidelines, modelling software documentation, pertinent HITL technical reports and references for additional reading.

By agreement between HITL and VPL Research, Inc., a cost-free site licence for the Macintosh modelling software package Swivel 3-D™ was granted to the Science Center for this study. The Technology Academy provided several Mac II computers for the students to use in constructing their virtual worlds at the Center. HITL provided students with a Swivel file containing a "protoworld", which consisted of two basic elements of a virtual world. The first element was the participant's virtual body, represented by a graphic head and hand. The virtual head is the position-responsive point-of-view, and the virtual hand is the digital analogue of the participant's physical hand, used for gesture commands such as "Fly" and "Grab." The second element was a ground plane extended to the maximum size that the rendering software could handle, for scale and orientation reference.

Each student research group had access to five computers for 8 hours a day. They worked in groups of two or three to a computer. They used a co-discovery strategy in learning to use the modelling tools. Teachers answered those questions that they could, but this software was new to them as well. Students were clustered inside a circle of computers, making it easy for them to share ideas and techniques as they created different elements of their virtual worlds.

On the last day of each session, a Science Center van took student VR researchers on the 15 minute ride to HITL at the Washington Technology Center, located on the campus of the University of Washington. At HITL, students were able to get inside their worlds using VR interface technology (we used RB2™ software on a Macintosh FX rendered by one Iris 320 VGX with a video-splitter; first-generation Eyephones™ were used for viewing and a right-handed DataGlove™ was used for gesture-command interactivity). Directly after their VR experience, students were given a polaroid photo of themselves wearing the head-mounted display and glove, taken as they explored their virtual world. They were then asked to fill out opinion questionnaires.

When evaluating the usefulness of VR, it is important to remember that commercial VR systems are currently at the "Kittyhawk" stage. They are awkward, limited in capability, and marginally reliable to use. There is lag between the participant's behavior and system update. Most head-mounted displays are very low in resolution; equivalent vision in the physical world is considered legally blind. Both the graphics and the sound elements are constrained by the power/expense of the system. Virtual worlds now are cartoons compared to the animated computer graphics we see in movies and on TV. The 3-D acoustic environment of VR is presently limited to a small number of sound elements. Despite these limitations, researchers are beginning to collect valuable information about the usefulness of VR for particular tasks and applications.

PEDAGOGICAL METHODOLOGY

HITL researchers wanted to see what these students were motivated to do with VR when given access to the technology in an open-ended context. We predicted that they would gain a basic understanding of VR technology as we gathered personal response and usability information from them. We expected that in using the modelling software, this group might learn to color, cluster, scale and link graphics primitives (cubes, spheres) to assemble simple geometric 3-D environments, and to specify simple interactions like "Grab a ball, Fly it to the box, drop it in."

Building a virtual world is an exacting task, and the students had only a week to complete their project. We considered the possibility that they might become overwhelmed with the task and choose to *play around* with VR, rather than learn enough to use it effectively. However, we considered it more probable that they would be sufficiently intrigued by worldbuilding to approach the task with directed energy.

The Science Center's goal was to give kids access to interesting new technology. VR student researchers were given an opportunity rather than an assignment to build a virtual world. Their experience was designed to be a hands-on student-driven collaborative process in which they would learn about VR technology by using it and learn about virtual worlds by design and construction. Their only constraints in this task were time and the inherent limitations of the technology.

WORLDBUILDING PROCESS

Monday: Each new group of students began their training with an introduction to VR by the Technology Academy Teacher , who is an experienced VR researcher formerly with NASA Ames. The students were given a presentation by one of the HITL researchers that included slides and videotapes. After lunch, students met together with their two teachers to plan their world.

The brainstorming session lasted an hour or so, and included discussions of several aspects of world design and implementation. They addressed conceptual design (what kind of world do you want? what do you want it to look like? what can you do in there?), system constraints (polygon budgets and movement/interaction limits) and 3-D graphics modelling principles (the relationship of context and objects, shaping graphical objects, linking objects to form complex constructions, relative and absolute scales).

The decision-making process for including objects in a world was straightforward: if you want it, make it and put it in. Everybody wanted to make something. Division of labor was addressed: one or two older kids typically volunteered to construct a particular context that elaborated on the simple plane of the protoworld. Everyone else agreed to add particular objects to the world, and a list of elements was made. The meeting adjourned, and everyone clustered around the computers to learn the modelling software.

Tuesday and Wednesday: Everybody made something to include. They demonstrated a range of modelling skills, creating a variety of objects from arbitrary blobs and blimps to objects like a carefully crafted table with turned legs, a petaled rose, an interactive sculpture, and a set of wine glasses with carafe. Students continued to construct elements and import objects from separate files into the virtual world context. The data structure underneath the objects was diagrammed and printed. They specified animation and interaction options (what could be grabbed, what would be animated) after the model was nearly complete.

Thursday: Technical details, such as checking scale and link constraints, were double-checked. Students assembled printouts of their written world description, graphical data hierarchy and constraints, and views of their graphics file with the objects identified by name.

At noon, the world disc was delivered to the Lab for programming, which involved importing the model into a separate dynamics programming package to add the specified interactivity and animation.

Friday: Students explored their worlds one at a time, while other group members watched what the participant was seeing on a large TV monitor. Although this was not a networked VR, it was a shared experience in that the kids "outside" the virtual world conversed with participants, often acting as guides.

Student researchers also toured the laboratory's facilities, observing VR research in progress. Each student was given a demonstration of 3-D sound, and had the opportunity to informally discuss speech recognition systems, position tracking systems, VR software programming, and artistic expression in VR with HITL scientists.

Each week followed roughly the same pattern, but there were discontinuities and exceptions. Successive student groups had the benefit of ongoing teacher training and experience, but they were also exposed to a decrease in teacher energy level over the course of an intensive seven weeks. Students' introduction to VR by different HITL researchers each week varied somewhat in form and content. There were several technical difficulties with the VR system in week four. Media was present twice during HITL site visits; while the kids seemed to take it in stride, it was perceived as intrusive by researchers. The Technology Academy Teaching Intern had sole responsibility for the students during the last two camp sessions.

PRODUCTS: Seven New Worlds

The virtual worlds that the students constructed are the most visible demonstrations of the success of the worldbuilding activity. A brief description of each world is drawn primarily from the students' written world documentation (see illustrations, Appendix A):

<u>Planetscape!!</u> "A futuristic world of craters and critters...included is a flying fish, various hovering monsters, and a rocket inside of a crater." The flat, crater-strewn landscape lay under a pink sky, and also contained small towers and two characters named "Bob" and Zeke" who could move along with the participant.

<u>Virtual Valley</u> "The valley is enclosed by surrounding mountains on the Northern and Southern sides. The horizon is dotted by suspended geometric objects. In the center...is a cubelike surrene [sic] lake with seaweed and a modern block sculpture. The valley floor...is marked with green trees, multi-colored buildings, and an observatory. [3-D sound] will enhance our Virtual World..." When entering the water a splash was heard; whenever something was grabbed, a metallic "klink" sounded; the students composed “eerie" music, to hear while flying through the blue-skies of the valley.

<u>Cloudlands</u> "We wanted to have a group world, but we each had something different that we wanted to do. We made our own cloud, or we created clouds in groups. We each had a small, separate world of our own." One cloud was a Western World with a colorful cactus, rocks and a 10-gallon hat; one contained a shark and a starfish, one was an elaborate house, one was a pair of "tie fighters" (Star Wars spaceships).

<u>Moon Colony</u> "Our project...shows what we think the moon will look like in the future. It consists of many mountains, futuristic buildings and spacecrafts. The transportation is a monorail [animated to follow its track]...another is a spacecraft...and a blimp. Downtown is located in a clear dome shaped building." A black sky loomed above.

<u>Neighborhood</u> "[It] consists of four different styles of houses...The first house is a futuristic house with one section below ground and two others above ground. All the rooms are furnished with 2-3 pieces of furniture. The second house is in the shape of a blimp, with the living quarters in the passenger section [where] there is a table with a rose and a vase...The blimp is large and blue and holds the room high above the earth. The third house has three rooms...a coffee table where there are three glasses and a bottle of champaign...a table, six chairs, six glasses and a pencil. Lastly, there is...a regular house, with a spaceship in the back yard. There are three rooms: a dining room with a fancy table; a computer room with a computer, and a bedroom with a toy and a book."

<u>Mid-Evil Space Station</u> "Our world...consists of trees, flowers, mountains, cosmic objects, castles, insects, swords stars, and a rocket...We picked this idea because we will never be able to experience the past...We also wanted to experience the future too, so we decided to make a mid-evil space station [shaped like a large castle high above the world] so we could have the experience of the past and the future together as one."

Mr. Mountain "Our world consists of a mountain with a nose, ears, and sunglasses [and a waterfall running out of the nose into a lake on the plain; inside the nose was a lake with a sunken treasure box containing money]. Inside of this so-called mountain we have a TV suspended in midair, a piece of dirty laundry, a farm with a pig, a cow, and an upside down farm house. We also have a very weird machine and a haunted house with a ghost [moving] outside...These things all are nestled in a green forest."

Characterizing across these worlds: they are complex, interestingly conceived and well-executed, as well as funny, imaginative and very different from each other. The conceptual sophistication of the worlds clearly varied, ranging from a fairly standard moon colony to "experiencing the past and the future together as one" to the addition of sound. The graphical skills of students varied even more widely, with objects ranging from blobs and "rocks" to delicate wineglasses and a table with turned legs.

The most interesting feature of the students' worlds, for HITL researchers, was their peaceful nature. While there were powerful creatures in each world, their interactivity was not specified to be aggressive. There was no interpersonal conflict imbedded in these constructions, no guns or bombs.

OBSERVATIONS

In collecting information on both student response and system usability, we used three different information gathering techniques. We hoped for both cross-verification across techniques and technique-specific insights. We videotaped student activities, elicited student opinions with surveys and collected informal observations from teachers and researchers. Each data source revealed different facets of the whole process.

Videotapes

HITL videotapes consist of 14 hours of students' VR experiences, and about 90 minutes of footage of discussions and conversations with two of the groups. The videos show the full body movement of the students. VR experiences at HITL are done while standing and moving within an area approximately 4' x 4'. Behaviors such as turning around, bending down, and reaching out are common. The impact of VR on kinesthetic learners deserves further research.

A view of what the participant was seeing in the virtual world could be seen on a large TV monitor. There were usually clusters of students nearby, talking with each other and with the participant while watching the monitor. The social behavior of participants varied widely: some carried on running conversations with the other students during their VR experience; some were silent, reporting that they had been distracted by the sounds outside their world.

The students' worlds were not programmed with sound, with the exception of week two. In an isolated instance of returning students, two older boys who had attended the first session, along with the 17-year-old Technology Academy Teaching Intern, spearheaded the second session's highly successful extension into 3-D sound. One of these boys had reported external distraction during his VR experience, and tried an experiment in the first week's world: he wore his Walkman into VR. In the second week, he not only participated in creating and specifying sounds to Virtual Valley, but attempted to use graphical elements (mountains) as sound buffers. This example of transferring knowledge of the physical world into assumptions about virtual objects is one of the few conceptual errors noted by researchers; he realized his mistake during a discussion of sound masking techniques.

Adding sound was substantial additional work both for students and for HITL programmers, and was not attempted by students in the following weeks. However, several students added their own sounds while in the virtual world by making motion noises as they flew, calling and talking to virtual characters, and making object-collision sounds.

The videotapes captured the sustained concentration of the students during their 10-minute VR experience, whether or not they verbalized. Their intensity of focus is more striking in review than it was at the time. Most of the videotapes don't display the high level of enthusiasm that was expressed in the student opinion questionnaires; they were fairly serious during their immersion.

The videotapes were an important source of system usability information. The students were far more active while exploring VR than adult participants tend to be. Frustrations included getting wound up in the cables and having to hold the heavy headmount in place when bending over to look down.

On most of the tapes, the students' conversations are clearly audible. Those who addressed other students were most often asking questions: what's that?, where am I?, where is...? The students outside the virtual world were usually able to answer the participant's questions without hesitation; they were seeing the same view on the high-resolution monitor. This indicates that the low resolution of the head-mounted display was inadequate for object identification and location recognition.

Despite these system constraints, the videotapes documented the students' remarkably fast accommodation to VR. They were adept at moving around in their worlds within the first minute or two when the system was working optimally. Interacting with objects was more difficult. Depth perception is difficult in low-resolution VR without the redundant cues that experienced world designers embed in their environment. Adaptation to the immaterial nature of virtual objects seemed quite easy for some students. One girl who seemed particularly at ease in VR bent over to fly down and tried to put her finger below her feet, through the floor of the lab; she seemed surprised that it was solid.

In looking at the tapes of different worlds, noticeable patterns could be detected in the students' ability to orient themselves and navigate through each world. It was easier for students to figure out where they were and to locate particular objects in some worlds than it was in others, apparently as a function of the design of the models [Bricken 1991b]. Worlds with clearly discernable landmarks around the periphery of the world (Virtual Valley, Moon Colony) were easier for students to orient themselves in than the world with many similar craters and one central landmark (Planetscape!!). It was difficult for students to know where they were inside houses where closed cubes were used for rooms (Neighborhood), and hard to locate objects set among a thick forest of uniform trees or nested inside of other objects (Mr. Mountain).

The Technology Academy provided a videotape documenting the students' brainstorming process while designing Mr. Mountain, as well as shots of the students using computers to build objects with Swivel.

Opinion Survey

The 59 students answered opinion surveys about their experience in Virtual Reality. The surveys include redundant questions designed to elicit reactions both to worldbuilding tools and to the VR experience. Three types of questions were asked: scaled (1 - 7); binary (forced choice); and open-ended.

The questions concerning students' personal response to the experience of VR and the average scores are as follows: (On questions where a 7 point scale was given, several students chose an answer higher than the allowed number. We counted those answers as sevens, but we wish to convey the enthusiasm with which the students responded.)

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 ...	(forced choice)
go into a virtual world (1) see a virtual world on a computer screen (0)	.95
go into a virtual world (1) play 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 on screen (0)	.98

The students were overwhelmingly pleased with VR technology. The raw averages are incredibly high and show the students' appreciation of the experience of VR. We believe that general student acceptance of this technology will be high.

Questions relating to worldbuilding tools measured students' comfort with Swivel 3-D and with programming in general:

	(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...	(forced choice)
build a Swivel world and go into it (1) go into a world that has already been built (0)	.76

These responses were not as unabashedly positive as the ones concerning overall feelings about VR. However, the average scores were still very promising and certainly positive enough to continue to explore the possibilities of world creation in an educational program. We feel that this response shows some displeasure with the tools or process of world building. Future studies can help indicate whether this reaction was due to the short amount of time the students had to use the tools, something inherently uncomfortable about the process, or some other reason.

We checked our assumptions about the redundancy of questions by looking at the correlations among the groupings that we had made. We found that the responses to the questions relating directly to the like or dislike of VR were highly correlated and that the responses to the questions relating to world building were also mutually correlated.

We asked other questions that indicate directions for future usability studies:

	(1: not good - 7: good)
Do you think VR would be a good learning environment?	5.7
Do you think VR would be a good place to play?	6.0
Do you think VR would be a good place to work?	5.0

	[1: extremely disoriented - 7: not disoriented]
Do you feel disoriented (dizzy or nauseated) inside the virtual world?	5.7
Do you feel disoriented (dizzy or nauseated) after leaving the virtual world?	5.5

Which is easier...	(forced choice)
seeing different views of the virtual world on the computer screen (0) seeing different views of the virtual world in VR (1)	.38

[Which is easier...]

moving Swivel objects on the computer screen (0)
moving objects in VR (1) .22

getting to a chosen location in a Swivel world on the computer screen (0)
getting to a chosen location in a virtual world inside VR (1)? .53

Would you rather explore...

a new place in VR (1)
explore a new place in the physical world (0)? .42

The questions concerning dizziness and the question about exploring new places are of particular interest. Dizziness can be related to specific aspects of the technology, or to particular individual differences. It was not significantly correlated to attitude toward the VR experience. Nearly half of the students expressed a preference to explore new places in VR rather than new places in the physical world. This response was far higher than we had predicted, and needs further investigation.

We also asked several questions that allowed for open-ended answers:

What was the one thing you liked best about VR?
What was the one thing you liked least about VR?
Now that you've been inside the virtual world you built, what would you change or add (if anything)?
If you could go into any virtual world that you can imagine, what would it be like?
What are the most important things you've found out about VR during your visit to the Laboratory?

We found patterns in the answers to the open-ended questions. With regard to what people liked best about VR, many of the students mentioned enjoying activities within VR such as being able to move and fly and pick up objects in the world ("flying without wings"; "you get to go anywhere"; "picking up objects"). Many others commented positively about the experience of being immersed in a virtual world ("experiencing a new place without going far"; "I felt like I was in space floating through the world I created" ; "Being IN it, not seeing it just on a screen"). Since this project also included the building of the worlds, we saw quite a few answers relating to the experience of world building ("we built our own world" ; "Going into my house and seeing my table"; "making your own world and going into it").

The answers to what the students liked least about VR verified our videotape observations, and perceptively echoed complaints by many professionals in the field. The resolution ("the screen was kind of fuzzy"), the hardware ("too many wires to get tangled in"), the software ("Swivel 3-D"), the lack of control ("couldn't move the right way"), and being dizzy ("feeling dizzy at the end") are all issues that are being actively explored in the development of VR systems.

The overwhelming answer to what students would change about VR is *more*. They want more objects, more movement, more color, more sound, more detail, and everything bigger ("More space and more buildings to pick up"; "more moving objects"; "more color and music" "More"). Again, this reflects the technical thrust of VR research.

We found the students' VR fantasies a fascinating part of the survey . Many students imagined utopias ("A pollution-free, evil-free, sadness-free, tree-filled world, like a almost perfect world"), historical worlds ("a medieval world with castles and towers"), outer space ("a forest on Mars"), water worlds ("underwater where I could swim alongside the dolphins and whales"), the physical world ("Virtual L.A."), games ("a world of stunts like bunjee cord jumping, sky diving, etc.") and elaborate visions that are difficult to categorize ("I would like to go inside a volcano, travel the lava tube and get blown out when it erupts."). The variety of answers showed tremendous imagination and indicated that VR appeals to the students' sense of adventure.

The students' responses varied on the most important things they found out about VR. Many commented on learning about what the VR state of the art was ("with a few more years of development it could be used for almost anything"; "it needs work"; "that technology is that advanced"). Others talked about how much fun it was ("it was really fun"; "it's AWESOME!!"). The most common comment was that they learned that world building and VR takes a lot of work, with many people also commenting that the effort was worth it ("how hard people have to work to gain such an experience, and how fun certain work can be"; "your hard work definitely pays off well"; "how much work it takes").

Informal Observation

Informal observations were useful for seeing social behavior and broad patterns of student response to VR. The following comments, collected from the notes of teachers and researchers, indicate directions for future research.

It was difficult to assess how representative these students were of the American school population. The group as a whole consisted of computer literate, predominantly white males, who had access to this relatively expensive summer camp. Further studies on more diverse populations are called for.

The students learned enough about the modelling software in 10 or 15 minutes to start creating objects. This is a much shorter learning curve than most adults demonstrate, an indication of students' ability to learn VR dynamics programming. Developmental differences were noticed in preferences for modelling particular elements of the virtual world: ages 10-12 were more comfortable with object construction; ages 13-15 were more comfortable with context design.

Both boys and girls seemed equally successful in creating elements of the world. Gender differences were noticed in the world design process during the one week that females outnumbered male students. The design approach in predominantly male sessions was goal-oriented; they made an initial decision on the content of their world and constructed objects according to plan. The predominantly female group (who created Mid-Evil Space Station) was process-oriented; they decided on a concept and then constructed a variety of items, choosing which ones to include in the world spontaneously.

Collaboration between students was highly successful, and resulted in strong group bonding. One week's group named themselves the Black Light SimSense Group, and submitted an additional survey reflecting their consensus on each answer. It seemed significant that everyone contributed something to each world, and that we didn't hear any negative comments from the students about each others' work.

SUMMARY

These students were fascinated by the experience of creating and entering virtual worlds. Across the seven sessions, they consistently made the effort to submit a thoughtfully planned, carefully modelled, well documented virtual world. All of these students were motivated to achieve functional competence in the skills required to design and model objects, demonstrated a willingness to focus significant effort toward a finished product, and expressed strong satisfaction with their accomplishment. Their virtual worlds are distinctive and imaginative in both conceptualization and implementation. Collaboration between students was highly cooperative, and every student contributed elements to their group's virtual world.

Students demonstrated rapid comprehension of complex concepts and skills. They learned computer graphics concepts (real-time vs. batch rendering, Cartesian coordinate space, object attributes), 3-D modelling techniques, and world design approaches. They learned about VR concepts ("what you do is what you get", presence) and enabling technology (head-mounted display, position and orientation sensing, 6-D interface devices). They also learned about data organization: students were required by the modelling software to link graphical elements hierarchically, with explicit constraints; students printed out this data tree each week as part of the documentation process.

Researchers learned which of the present VR system components were usable, which were distracting, and which were disfunctional for this age group. Our conclusion is that improvement in the display device is mandatory; the resolution was inadequate for object and location recognition, and hopeless for perception of detail. Another concern is with interactivity tools: manipulating objects with the DataGlove™ was *not* natural; discrete gestures triggered particular commands but there was no actual manipulation of objects. The head-mounted display has since been boom-mounted for lighter weight and less intrusive cable arrangement.

Students, teachers and researchers agreed that this of exploration VR tools and technology was a successful experience for everyone involved. Most important was the demonstration of students' desire and ability to use VR *constructively* to build expressions of their knowledge and imagination.

It is our preliminary conclusion from this study that VR is a significantly compelling creative environment in which to teach and learn. Over their years in school, students could create a universe of learning worlds that reflected the evolution of their skills and the pattern of their conceptual growth. Evaluating comprehension and competence would become experiential as well as analytical, as teachers explored the worlds of thought constructed by their students.

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