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Student-Built Virtual Environments

Abstract

Students in grades four through twelve from fourteen schools learned to build their own immersive virtual environments (VEs). This required them to decide on the theme of their VE, to determine what objects to place in it and what behaviors these objects would exhibit, to model their objects using CAD software, to specify the form and function of the VE for professional programmers to use as they assembled the VE, and to perform assigned tasks when they visited the VE. Although the level and nature of student activity varied from school to school, the students were generally very successful. The VEs they constructed revealed a great deal about how they constructed an understanding of the content their VE represented. Data from a questionnaire showed that they enjoyed building and visiting their VE, and that their enjoyment, ability to work in the VE, success, and their sense of presence were all interrelated. Data from a small subset of students showed that building a VE improved low-ability students' (but not high-ability students') understanding of the VE's content. These findings were interpreted within a framework built from constructivist theories of learning and understanding.

1 Introduction

Over the last three years, our laboratory has taught students in grades four through twelve to build virtual environments (VEs). This article presents a rationale for this activity that draws from theories of knowledge construction and from an understanding of how students use symbol systems. It then describes our VE-building project, presents some of our findings, and draws conclusions about the value of VE-building activities.

In this article, a VE is understood to be an immersive, three-dimensional environment created in real time from a database. The database consists of 3-D objects modeled by CAD software. These objects are programmed to behave in certain ways as they interact with each other and with a student visiting the VE. The student wears a helmet in which the objects are displayed stereoscopically in two eyepieces. The student's head is tracked electromagnetically so that the computer can redisplay the objects from the changing viewpoint in real time. The student holds a wand, whose position is also tracked. The wand appears in the field of view as a hand or tool. By gesturing with the wand and pressing buttons on it, the student can move around inside the VE, pick up objects and

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interact with them in a number of ways. Stereophonic sound completes the system.

1.1 Constructivism

We can justify having students build a VE in order to learn something by the principles and practices of learning and teaching that are collectively referred to as *constructivism* (Dede, 1995; Duffy, Lowyck, & Jonassen, 1993; Winn, 1993). Constructivism holds that students learn best when they build their own understanding of content by directly interacting with it, rather than receiving content, predigested and prestructured, from a teacher or text. Constructivism also stresses that understanding is arrived at largely through consensus-building as students interact with each other in the pursuit of meaning. Research has demonstrated the effectiveness of constructivist approaches to learning for both complex, ill-structured content, like literary theory (Spiro, Feltovich, Jacobsen, & Coulson, 1992), and more rule-bound content, like mathematics (Cognition and Technology Group at Vanderbilt, 1993) and science (Chinn & Brewer, 1993; Windschitl & André, 1998).

Research into constructivism's contribution to learning leads to the conclusions that students learn more when they must invest mental effort in finding and structuring content for themselves, when they take responsibility for building conceptual models that are both consistent with what they already understand and with the new content, and when they do this collectively with other students. The successful adaptation of old knowledge to new leads to understanding and, when it is the responsibility of students to work at achieving this accommodation, success is also intrinsically motivating.

Our project took constructivism one step further. As well as constructing knowledge by interacting with objects in a VE, our students constructed knowledge by building the VE in the first place. The design and construction of objects, such as robots and computer-controlled Lego® devices, with behaviors and the ability to interact, is what Harel & Papert (1991) have called "construct*ion*ism" (as opposed to "construct*iv*ism"). Studies of constructionist approaches to learning show that the expression of mental models as objects that can be inspected and handled offers powerful advantages for solving problems and building understanding (Harel & Papert, 1991; Kafai & Resnick, 1996).

1.2 Symbol Systems

Another reason for the success of VEs arises from their extensive use of symbol systems that are not frequently available to students in the classroom. Foremost among these are graphics: still and animated pictures, simplified visual analogs, schematics, and pictorial metaphors. The study of how graphics like these contribute to learning has a long history. (See reviews in Mandl and Levin (1989), Schnotz and Kulhavy (1994), and Willows and Houghton (1987).) Generally, illustrations are most useful when they have functions other than simple decoration, such as illustrating what something looks like or how it works (Levin, Anglin, & Carney, 1987). Graphics do not require students to use verbal and abstract reasoning skills to construct knowledge, offering alternative routes to success for students who are weak in these abilities. Also, representing functional relationships by spatial location has been shown to be effective for helping students understand processes, such as how pulley systems work (Larkin & Simon, 1987) and abstract relationships, like kinship in families (Winn, Li, & Schill, 1991). This is because relationships—such as between load and effort in pulley systems or between the self, siblings, and cousins in family trees—can be determined simply by inspecting a visual display and do not have to be computed from nonspatial information such as text.

When objects are also animated (as they often are in VEs), their behavior and interactions can be used to illustrate processes that take place over time. In many studies, Rieber (summarized in 1994, chapter 6) has demonstrated that computer animation is useful particularly when real or metaphorical motion and trajectory are important concepts. Animation of objects that occurs because of student actions on them is particularly effective.

1.3 Prior Research

The feasibility of VE construction by children and its benefits for arousing interest in VR and computers were demonstrated by Bricken and Byrne (1993). Students attending a science camp spent a week learning about VR and designing, building, and visiting their own VEs. The VEs were imaginative, whimsical, and demonstrated a high level of technical and creative skill. However, Bricken and Byrne did not study how building VEs might contribute to students' understanding of what the VEs represented.

Osberg (1997a, 1997b) applied principles of constructivism and took advantage of many of the properties of graphics when she studied student construction of VEs as a way for them to learn about wetlands ecosystems. Seventh-grade students built VEs that embodied concepts and principles of the nitrogen, carbon, water, and energy cycles. The students selected content, chose which objects to put into the VE, selected metaphors for phenomena that have no directly perceptible form (such as the processes by means of which nitrogen is fixed), built the objects, specified their behaviors, and visited the finished VE to demonstrate what they had learned. Osberg reported that building the VEs significantly improved the students' knowledge of factual information and their understanding of the concepts and principles they studied. She concluded that constructing VEs requires students to use a number of strategies that they normally cannot exercise in a traditional classroom, that giving students "ownership" over their own learning is highly motivating, and that constructing knowledge for themselves makes what they learn more permanent.

The project reported here extended Osberg's work in several ways. First, we were interested in the choices students would make to represent objects and processes they wished to place in VEs. How would students go about building a VE that was intended to help their peers understand the material the VE represented? Second, we needed to confirm earlier findings about visiting VEs that enjoyment, presence, and the ease of navigation are related (Taylor, 1997; Winn, 1995). Finally, we were curious about whether constructing VEs would help students who normally did not do well in class. We expected that building VEs to express understanding would allow less able students to use concrete and graphical symbol systems, which they would normally not use, to communicate their ideas.

2 Method

2.1 Subjects

The project involved 365 students in grades four through twelve, from fourteen schools. The schools represented a good cross-section of urban and rural, wealthy and poor, and ethnically diverse communities. Although we worked with intact classes and had no say about which students would take part, there was approximately the same number of males and females in each class. Student activities varied from class to class. In some classes, students were assigned particular roles by their teacher, such as "project manager," "content specialist," "graphic designer," or "modeler." In other schools, the students played several or all of these roles.

2.2 Procedure

At the beginning of the school year, teachers taking part in a larger project to bring VR to their classrooms—the Virtual Reality Roving Vehicle, (VRRV) project (Winn, 1995)—were invited to submit short proposals to have their students build VEs. Fourteen proposals were received. Six of these proposals were from elementary schools, five from middle schools, and three from high schools. Each school proposed to build a different VE, which are described below.

We provided three all-day workshops for teachers. During the first, project staff gave presentations about virtual reality and described possible educational applications. The teachers then broke into groups and "brainstormed" the projects they proposed to do. (Most of the teachers had already experienced a VE as part of their orientation to the VRRV project.)

The second workshop (offered twice) was an intensive introduction to the modeling software, (Macromodel® from Macromedia Inc., running on Macintoshs). We held this workshop in a school computer lab. It was almost entirely "hands-on," with one project staff person for every three teachers. At the end of this workshop, it was apparent to most of the elementary teachers that it would be too difficult for their students to master the software and build the VE. We therefore decided that all the elementary students (and, by choice, students from one middle school) would contribute to the same VE, "Tree World." Project programmers would build most of the VE, following the students' design, with students adding objects that were not essential to making it work. (This VE is described below, with the others.)

The third workshop consisted of presentations and discussion on how to use VEs to help students learn, instructional design, assessment, and project management. At the end of this workshop, each school set its schedule and milestones so that project staff could plan their school visits.

We took a four-step approach to constructing VEs: planning, modeling, programming, and experiencing. The entire process took from six to ten weeks with numerous visits by project staff to the students and their teachers, with considerable variability from school to school. During the planning phase (following constructivist tenets about collaboration), students worked in groups to make decisions about how the VE should look and behave. They were given the task of constructing a VE in which other students could learn the content. This required them to choose content, to find ways to show objects, and to make metaphors for invisible objects and procedures. Modeling required the students to learn the modeling software we used for the project, to design their objects on paper, and then to draw them in three dimensions on the computer. Project staff did the programming, which involved assembling the objects into the VE, following the students' instructions, and imbuing the VE with the intended behaviors. For the experiencing phase, students visited the VEs they had created. They were given specific tasks to perform. After performing these tasks (which took from ten to fifteen minutes), students completed knowledge post-tests and a questionnaire.

2.3 Data Sources

The most interesting sources of data were the actual VEs that the students built. While we made no attempt to analyze or compare them formally, they form the basis for a number of observations and conclusions that we offer below.

Students completed a questionnaire that consisted of 24 five-point scales that solicited student ratings in a number of areas including enjoyment both of building and visiting the VE, the sense of "presence" in the VE (the extent to which students felt they were really in the VE and not in the classroom), and potential impediments to learning (such as difficulty seeing and moving around in the VE and queasiness). The questionnaire for the elementary students was slightly different from the one used with the middle- and high-school students because the younger students played a different role in building their VE.

In one middle school and two high schools, students in other classes at the same grade level who were not working with us were studying the same content as the VE builders. This gave us the opportunity to assess, albeit not in a controlled experiment, the contribution of building VEs to learning. The students in these three schools took teacher-constructed post-tests over the content they had been studying. Because each group of students built a different VE, and each teacher therefore wrote a different post-test, the scores were first standardized to a mean of 50 and a standard deviation of 25. Students also took a test of general ability, Raven's "Progressive Matrices" (Raven, 1958). Scores on this test were converted to percentiles for analysis, using age-based norms. These students visited the VE built by their peers.

2.4 The Virtual Environments

Here we describe the VEs that the students constructed. They vary in detail, complexity, completeness, and success.

2.4.1 Tree World. For reasons given earlier, this VE was used with all of the elementary schools and one middle school. The goal is for students to make a sickly tree healthy by providing it with sunlight, water, and nutrients. To provide sunlight, they must fly into the sky and push aside a cloud that obscures the sun. To provide water, they must push aside a boulder that blocks the stream flowing by the tree. To provide nutrients, they offer grass to a cow, which eats the grass and "fertilizes" next to the tree. As they complete each operation, the tree appears more healthy. Its bark changes from gray to brown, its branches no longer sag, and leaves appear. Although the students decided what needed to happen to make the tree healthy, project programmers built the basic world, the tree, sun, cow, and boulder. The students provided creatures that contribute to the well-being of trees (such as pollinating insects) and whose well-being depends on trees (such as squirrels and birds).

2.4.2 Space Station. This VE was built by middle-school students and illustrates ways in which astronauts recycle resources in space. The space station consists of two compartments connected by a passageway. It is equipped with the apparatus and furnishings that one expects in a space station. In the first compartment, students use and recycle water. They take a shower, collect the water they use, put it into a recycling device, and drink the recycled water from a plastic bottle. The second compartment allows students to "scrub" (recycle) carbon dioxide to produce breathable oxygen. This requires them to grab CO_2 molecules and place them in the scrubber. The converted molecules have different color and structure.

2.4.3 Castle. This VE, also built by middle-school students, depicts a medieval castle, surrounded by a moat. Students may operate the wheel that lowers the drawbridge and enter the castle, where they may visit a number of rooms, which are appropriately furnished in the manner of the day, with an open hearth for cooking, a large table and stools for dining, and so on. Swords and other weapons hang on the walls. The students may take these down and handle them, though they have no real functionality. (You cannot cut up the furniture with a sword, for example.)

2.4.4 Rain Forest. Another middle-school world, this VE tells the story of the destruction of the rain forest. Students first see a lush, green Earth from space, with South America prominently in view. They fly down to the Amazon basin. Here, they initiate a sequence of actions. First, bulldozers appear that destroy the trees and the creatures that live in them. The trees are replaced by cattle that graze on the cleared land. The students then "convert" the cattle into hamburgers. From space again, the Earth appears as a brown desolate sphere with a large dollar sign over it. (The first author showed a tape of this VE to a group of high-school students in São Paolo, Brazil. A heated argument ensued about the right of American students to criticize Brazil for cutting down its forest when Americans cut down many of their trees over 100 years ago!)

2.4.5 Endangered Species. This middle-school VE was less complete. Students visit an island where they may interact with its creatures, but this interaction with the creatures causes their demise. (For example, handling a bird turns it into a skeleton.)

2.4.6 Washington State. High-school students constructed a virtual map of Washington with major natural features (the Cascade Mountains, the Columbia River, and so on) and man-made features (cities, highways, the Tacoma Narrows Bridge, their school, etc.). As students fly around the state, they may "interrogate" these features. When they do so, a label appears identifying them. Texture mapping is used extensively.

2.4.7 Computer. This was another high-school project. Students have to install a CPU, disk drive, and memory in their correct positions on a computer motherboard. They find the components they need on a shelf. Color-coding and feedback are used extensively to help them.

2.4.8 Tides. An intractable bug prevented completion of this VE. High-school students observe how the moon causes tides as it orbits the Earth. They may change their point of view at will and observe from different angles.

3 Findings

3.1 Observations about the VEs

It is clear that students were able to make decisions about the content to include in their VE, what objects to use to illustrate it, what metaphors to use when necessary, and what behaviors and interactions the objects should exhibit. The following features are common to more than one VE and provide insight into how students constructed knowledge about their topics.

3.1.1 Metaphors. We can observe two kinds of metaphor in the worlds the students built: virtual objects that stand for other objects or processes, and virtual objects that stand for objects or processes that are not normally accessible to the senses. (As examples of the former, in the rain forest VE, hamburgers stand for the "end product" of clearing the forest for beef production. Skeletons replace live creatures in the endangered species VE to indicate their fate at the hands of mankind. Cow poop represents the nutrients needed to make trees grow in the tree VE. As examples of the latter, in the space station VE, molecules of different colors that represent CO_2 and breathable oxygen are examples of metaphorical representations of objects that are not directly accessible to the senses.)

These observations suggest that our students were capable of using metaphors to construct and express their understanding of concepts and principles that are difficult to represent directly. However, like Osberg (1997b), we observed that metaphors tended to cause students to undergeneralize principles. For example, when elementary-school students were asked how trees get nutrients, many replied that nutrients come from cow poop. The expression of understanding in terms of the metaphorical object rather than the general principle that the metaphor stands for is a clear example of what Spiro et al. (1992) have called "reductive bias": the oversimplification of content to make it easier to understand. Reductive bias is less pronounced in older students. However, we think that, for students of all ages, metaphors must be used with caution and students must be led to the general principles the metaphor represents as quickly as possible.

3.1.2 Transformations. A number of the VEs tell "stories." These narratives illustrate the students' use of transformations over time to show processes at work. In the space station, students' actions cause wastewater to be transformed into drinkable water and CO_2 into oxygen. In the rain forest, trees are transformed into cows which are, in turn, transformed into hamburgers. Endangered species are transformed into skeletons. A sick tree is transformed into a healthy one.

The unprompted use of narrative to describe changes that take place in the natural world suggests two things. First, since the narratives correctly describe the transformations, we conclude that the students understood the phenomena their VEs represented. Similar to their use of metaphors, though, we found that some students, when asked, described transformations in terms of their stories, rather than in more general terms. We need to take care to help them understand general principles, such as the demands for food leading to clearing the rainforest, not just the demand for hamburgers causing the bulldozing of trees. Second, narrative appeared to be a useful form to describe cause and effect for these students. They appeared naturally to adopt a rhetorical form that easily describes a chain of events, each causing the other.

3.1.3 Visiting Other Places. Two of the VEs reveal places that students cannot visit in the real world. The medieval castle reproduces the appearance and atmosphere of that place with considerable accuracy. While the actions the student may perform there are limited, effort has been put into re-creating a number of telling details, such as the way people cooked and ate food, and the weapons they used. Likewise, the space station is accurately rendered, both externally and internally, based on NASA pictures. Equipment and furnishings are similar to what one would expect to find in a spacecraft.

The accurate representation of the appearance of a place shows that students have learned how to describe it and can remember what it looks like. Although learning a description is not as difficult as learning a process, perhaps represented by a metaphor, it was nonetheless important that our students demonstrated their ability to build accurate descriptions in their VEs.

3.1.4 Spatial Relations. Two of the VEs exploit spatial relations particularly well. The Washington VE helps students learn the appearance and location of natural and man-made features in the state. By correctly scaling the map of the state and fixing the rate that visitors may "fly" over it, the students made a VE that accurately mapped the real territory. This allowed those visiting the VE to use time, distance, and direction of travel to find places in Washington. The tides VE, though unfinished, uses the ability of students to observe the location of the moon and the location on Earth where it has its effect on tides. Their ability to change their point of view adds to their knowledge of how tides work.

These two VEs illustrate how students mastered two ways to use spatial relations. First, the students who built the State of Washington VE used space to illustrate factual information about the location of places. This is obviously a standard way to use maps for learning about territories. More interesting is the use of space in the tides VE. It is extremely difficult to learn how the moon's gravitational pull causes tides without some kind of spatial representation. Seeing the moon from space, moving around the earth, with gravity represented as arrows—and the ocean, exaggerated in depth, blanketing the earth—makes it easy to understand why there are two tides a day and why one is always higher than the other. The student can simply observe how the layer of ocean "thickens" on the sides towards and opposite the moon and "thins" on the other two sides. Our students' use of this representation shows that they understood the phenomenon.

3.1.5 Actions with Feedback. The computer VE, and to some extent the Space station VE, guide student actions with feedback. The simplest form of feedback (the default in fact) is that a wrong action produces no results. For example, if a student visiting the space station places used shower water anywhere but the recycling apparatus, nothing happens. Typically, the student will repeat the operation and, unless the student realizes the mistake, will become frustrated. Different audible tones or sound effects for correct and incorrect actions provide better indications to students about the correctness of their actions. These were used as students worked in the computer VE to place components on the motherboard. In the tree VE, visible feedback was used extensively. Not only did the appearance of the tree improve as the student completed each operation, but the light intensity increased when the sun shone and the water level in the stream rose when the boulder was moved aside, releasing the water. In some of the more narrative VEs, like the rain forest, only one action was possible at each step—the program did not branch—so the need for feedback was less important. And in cases in which the VE simply provided information when students requested it, as in the State of Washington VE, or where actions were not correct or incorrect, as in the Castle VE, corrective feedback was not necessary at all.

What is interesting about the use of corrective feedback, limited though it was, is that it required students building a VE to anticipate the kinds of errors that other students using the VE were likely to make. Popular wisdom holds that the best way to learn something is to teach it to someone else. By anticipating errors, our students were learning by teaching. It is worth noting that, in a subsequent project, we have had students work with us as instructional designers, a role at which many excel and enjoy.

3.1.6 Scale and Position. A number of the VEs took advantage of the ability of VEs to change the scale at which a student observes the VE and operates within it and the position in space the student may take in it. A good example of this is the Washington VE, where students may visit any location in the state they want and may travel from one end of the state to the other in less than a minute. The tides VE shrinks the earth and moon to a size where students may observe them working as a system. (Or, the student may think they are viewing the earth and moon from afar after "zooming out" into space.) Similarly, the view of earth at the start and finish of the rainforest VE is from orbit. And in the computer VE, you "shrink" in size so that you may walk or fly around inside the machine to place larger-than-life components in their correct places.

These observations tell us as much about what students learned about VEs as it does about their understanding of content. What is interesting, though, is that it seems that they have a good sense of how to match a VE's ability to vary scale and a participant's position to fit learning requirements for various concepts and principles. This in turn requires an understanding of the content and how best to learn it. Thus, we see effective variations of scale and position in their VEs as evidence that the students understood the content.

3.2 Numerical Data: Questionnaire

Because the elementary-school students answered a slightly different questionnaire from the secondary students (middle and high school), elementary and secondary questionnaires were analyzed separately. Data from the questionnaires confirmed findings from earlier studies about the enjoyment, sense of presence, and the ability to navigate and work in a VE (Taylor, 1997; Winn, 1995). Ratings of statements on five-point scales provided the following results.

Ninety-four percent of the elementary students enjoyed making Tree World, rating the relevant statement either 1 or 2 out of 5, and by the same criteria, 98% enjoyed visiting it. For the secondary students, 81% enjoyed building the VE and 85% enjoyed visiting it. Sixty-three percent of the elementary students reported experiencing a high level of presence (rated 1 or 2 out of 5) when they visited the VE, and 15% reported some degree of malaise (dizziness, queasiness). For the secondary students, the ratings were 57% for a high level of presence and 11% for malaise. Most elementary-school students had little difficulty navigating inside the VE, with 68% rating ease of navigation 1 or 2 out of 5. Fifty-nine percent of the secondary students also rated navigation easy.

Cross-tabulations revealed some interesting relationships among presence, enjoyment, and the ability to work in the VE. (For each of the following results, Chi-square was significant beyond the 0.05 level.) Elementary- and secondary-school students who reported a high level of presence enjoyed both building and visiting the VEs more than students who reported less presence. Elementary students who reported a high level of presence also said they understood—better than students reporting less presence—what they were supposed to do in the VE and were better able to do it. Interestingly, this was not the case with the secondary students. Elementary students who reported malaise enjoyed visiting the VE less and found it harder to navigate and work in it. Again, this was not the case for secondary students.

In many schools, teachers and project staff encouraged students to collaborate with each other. We therefore looked at whether students who reported working with other students enjoyed their work more and felt they performed better. Two questions on collaboration sought ratings on how much students helped other students and how much they were helped by others. Significant associations were only found for the first questions (the extent to which students helped others). Elementary students who reported helping other students found it easier to perform their task in the VE. Secondary students who helped other students reported a greater enjoyment building and visiting the VE, found it easier to work and navigate in the VE, and understood better what they were supposed to do in it.

3.3 Numerical Data: Tests of Learning

We were interested in whether building VEs would help less able students understand content. Students in the one middle school and two high schools, where we measured learning, were blocked on ability based on their Raven's scores, with students scoring in the middle third of the range of scores excluded from the analysis. (Complete data were available for 45 students.) Post-test scores (reported here as percentages) were submitted to a two-way ANOVA involving "VE-building" and "Traditional" groups crossed with high and low ability. There was no main effect for group. However, the interaction of group with ability approached significance, $F_{(1, 44)} = 2.91$, $p < 0.10$. Follow-up ANOVAs showed that low-ability students who built a VE ($M = 68.62\%$, $SD = 20.75$) significantly outperformed those studying in the traditional way ($M = 42.55\%$, $SD = 26.28$), $F_{(1, 44)} = 8.67$, $p < 0.01$. For high-ability students, there was no difference in performance ($M_{\text{VE}} = 60.16\%$, $SD = 18.75$, $M_{\text{Traditional}} = 60.89\%$, $SD = 19.36$). VE-building only helped low-ability students.

4 Discussion

The most important finding of this study is that the students were able to design a VE, model the objects to put in it, and perform tasks successfully when they visited it. Of course, not all students were equally successful, nor did each student contribute equally to the project. Collectively, though, they were extremely successful and worked very hard to complete their tasks.

The VEs themselves reveal a lot about the way the students thought about the subject matter they were working with. We mentioned above that constructivism holds that students construct understanding for themselves by interacting with objects and processes in a learning environment and in collaboration with other students. In all of the VEs built by students for this project, knowledge construction was possible because actions could be performed and their consequences observed. Clearly, the extent of interactivity varied from VE to VE. But this claim is true, to some extent, in every VE.

The focus of this project was on learning by building—not visiting—VEs. Constructivism holds that knowledge construction must start with some pre-existing knowledge upon which to build. The VEs that the students built for this project show how understanding new concepts and principles occurs as the requirements of designing and building the VEs force an extension and modification of pre-existing knowledge. For example, students who built the Washington VE came to the project with some knowledge of the locations of features within the state. Building the VE required the students to extend this knowledge by relating it to the entire state and to do so with considerable accuracy of position and scale. Students who built the space station VE came with an idea of what astronauts do and with some notions about what life in space must be like. However, requiring them to think about recycling as a way to extend life support extended this knowledge into new realms of understanding. Only when they used metaphors did some students fail to extend their pre-existing knowledge to any great degree. We suggested that this is because metaphors tend to constrain rather than extend understanding, unless students can quickly see through the metaphor to the concept or principle that underlies it.

The questionnaire data confirm that students enjoy building and visiting VEs. Their enjoyment, success at performing assigned tasks, and their ability to find their way around in the VE improve if their sense of presence is high. Not surprisingly, if they feel ill, they will not do as well on assigned tasks and will not enjoy themselves.

Two findings from the questionnaire data deserve further comment. The first is the overall lower ratings by secondary students on enjoyment, presence, and ability to work in the VE. This was also noted in an analysis of ratings on a similar questionnaire from roughly 3,000 students in the larger VRRV project (Winn, 1995). The explanation may be that working with VR is less "cool" for older students, or that younger students adapt more easily to VEs, perhaps because they are more easily convinced of its reality. These explanations need to be tested in further studies.

The second finding is the relationship between helping other students and enjoyment, presence, and the ability to work in the VE, particularly among secondary students. First, we must remember that secondary students contributed much more to their VEs than the elementary students, who all worked on the same VE. Where collaboration occurred, it would therefore have a greater impact on the secondary students. That said, we can suggest that students who helped others a lot did so because their greater skill with the technology and associated tasks was known to the students they helped. This means that they could be expected to work more effectively building a VE in the first place and would have reported greater presence, enjoyment, and success whether they helped others or not. Our results did not establish, however, that those receiving help from these "experts" improved their experience in the same ways. Further study of how students can help other students understand and enjoy VEs is required.

The results of the statistical analysis of the post-test scores from the three classes of secondary students suggest that VE-building leveled the playing field for students with lower general ability. This is encouraging, because it suggests that allowing students to express what they know using concrete and physically manipulable symbols for even the most abstract of concepts and principles can be an effective way for them to construct knowledge. However, the sample was small, and experimental controls were not possible in our project. This finding needs to be replicated in a controlled experiment.

To conclude, this project has shown that students can construct VEs in such a way that they come to understand the concepts and processes that the VEs describe.

From a limited set of data, this appears to be more the case for students with a low general ability (as measured by a standardized test). Collaboration among students also has a role to play. Presence contributes to enjoyment and to the ability to move around and perform tasks in a VE. Not surprisingly, malaise has the opposite effect, although only a small percentage of our students reported discomfort in the VE.

Controlled experiments are needed to confirm a number of our findings. In particular, we need to measure understanding, from a larger group of students with varying abilities, in order to identify the extent to which constructing VEs and using a variety of symbol systems help them learn. We need to establish causal relationships between presence, ability to work in a VE, and learning. We need to examine more carefully when and why collaboration among students helps them learn.

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