ScienceSpace: Virtual Realities for Learning Complex and Abstract Scientific Concepts

Chris Dede
Graduate School of Education
George Mason University
Fairfax, VA 22030
(703) 993-2019
Cdede@gmu.edu

Marilyn C. Salzman
Psychology Department
George Mason University
Fairfax, VA 22030
(703) 352-8375
Msalzman@gmu.edu

R. Bowen Loftin
Mail Code PT4
NASA/Johnson Space Center
Houston, Texas 77058
(713) 483-8070
Bowen@gothamcity.jsc.nasa.gov

Exemplary pedagogy in science education should develop learners' abilities to intuitively understand how the natural world functions before inculcating the formal representations and reasoning skills that scientists use. In other words, fostering in students the capability to qualitatively predict the behavior of the objects in the universe is initially more important than teaching them to manipulate quantitative formulas. Through using multisensory immersion in virtual realities customized for education, we believe that complex, abstract material now considered too difficult for many students—and taught even to advanced learners only at the college level—could be mastered by most students in middle school and high school.

The virtual reality interface has the potential to complement existing approaches to science instruction through creating immersive inquiry environments for learners' knowledge construction (Dede et al, 1994). By themselves becoming part of a phenomenon (e.g., a student becomes a point mass, undergoing collisions in a frictionless artificial reality), learners gain direct experiential intuitions about how the natural world operates. Good instructional design can make the aspects of virtual environments useful in understanding scientific principles most salient to learners' senses.

As one illustration, in two-dimensional Newtonian microworlds students often ignore objects' velocities, instead focusing on position. In a virtual reality environment, learners themselves can be moving, centering their attention on velocity as a variable; and designers can heighten this saliency by using multisensory cues to convey multiple, simultaneous representations of relative speeds. The novel perspective of oneself experiencing and shaping a natural phenomenon, instead of acting as a passive observer, is intrinsically motivating. Transducing data and abstract concepts (e.g., acceleration) into multisensory representations is also a powerful means of enhancing understanding. Under these conditions, learners may be able to construct mental models of phenomena that have no counterpart in their everyday experience.

The Virtual Worlds of ScienceSpace

Since February, 1994, our project team has worked collaboratively to build "ScienceSpace," a collection of virtual worlds designed to aid students in mastering challenging concepts in science. ScienceSpace now consists of three worlds—NewtonWorld, MaxwellWorld, and PaulingWorld—in various states of maturity. NewtonWorld provides an environment for investigating the kinematics and dynamics of one-dimensional motion. MaxwellWorld supports the exploration of electrostatics, leading up to the concept of Gauss' Law. PaulingWorld, the most recent addition, enables the study of molecular structures via a variety of representations.

All three worlds have been built using a polygonal geometry. Colored, shaded polygons and textures are used to produce detailed objects. These objects are linked together and given behaviors through the use of NASA-developed software that defines the virtual worlds and connects them to underlying physical simulations. Interactivity is achieved through the linkage of external devices (e.g., a head-mounted display) using this same software. Finally, graphics rendering, collision detection, and lighting models are provided by other NASA-developed software. The key hardware items used are a high-performance graphics workstation with two video output channels; a color, stereoscopic head-mounted display; a high-quality sound system; a magnetic tracking system for the head and both hands; and, in some cases, a haptic display. Interaction in these worlds is principally carried out with a "3-Ball," a three-dimensional mouse.

Description of NewtonWorld

NewtonWorld is intended for exploration of Newton's Laws of Motion as well as the conservation of both kinetic energy and linear momentum. In NewtonWorld, students spend time in and around an activity area, which is an open "corridor" created by a colonnade on each side and a wall at each end. In one-dimension along the axis of the corridor, two balls move and rebound from each other and the walls. Students interact with NewtonWorld using a "virtual hand" and a menu system, which they access by selecting a small 3-Ball icon in the upper left corner of the HMD's display. Learners can launch and catch balls of various masses and can "beam" from the ball into and among cameras strategically placed around the corridor. The balls move in one dimension along the corridor, rebounding when they collide with each other or the walls. Equal spacing of the columns and lines on the floor of the corridor aid learners in judging distance and speed. Signs on the walls indicate the presence or absence of gravity and friction.

Multisensory cues help students experience phenomena and direct their attention to important factors such as mass, velocity, and energy. For example, potential energy is made salient through tactile and visual cues, and velocity through auditory and visual cues. Currently, the presence of potential energy before launch is represented by a tightly coiled spring, as well as vibrations in a special vest users wear that communicates haptic sensations. As the ball is launched and potential energy becomes kinetic energy, the spring uncoils and the energy vibrations cease. The balls now begin to cast “shadows” whose areas are directly proportional to the amount of kinetic energy associated with each ball. On impact, when kinetic energy is instantly changed to potential energy and then back to kinetic energy again, the shadows disappear and the vest briefly vibrates. To aid students in judging the velocities of the balls relative to one another, we have the columns light and chime as the balls pass. Additionally, we provide multiple representations of phenomena by allowing students to assume the sensory perspectives of various objects in the world. For example, students can become one of the balls in the corridor, a camera attached to the center-of-mass of the bouncing balls, or a movable camera hovering above the corridor.

To guide the learning process, we provide scaffolding that enables learners to advance from basic to more advanced activities. Students begin their guided inquiry in a world without gravity or friction, allowing them to perceive physics phenomena that are otherwise obscured by these forces. They can launch and catch balls of various masses and can view the collisions from several viewpoints. These activities provide an immersive experience of often counter-intuitive phenomena. By instructing students to make predictions about upcoming events, directly experience them, and then explain what they experienced, we encourage learners to question their intuitions and refine their mental models. We have developed detailed human subjects protocols that lead students through a progressive sequence of learning activities, carefully documenting their knowledge before and after these experiences.

Description of MaxwellWorld

Our second virtual world was built to incorporate "lessons learned" from usability studies of NewtonWorld. This world has been designed to enable the examination of the nature of electrostatic forces and fields, to aid students in understanding the concept of electric flux, and to help them empirically "discover" Gauss's Law. MaxwellWorld occupies a cube approximately one meter on a side with Cartesian axes displayed for convenient reference. The small size of the world produces large parallax when viewed from nearby, making its three-dimensional nature quite apparent. Menus and the 3-Ball are used for interaction in this world.

Unlike NewtonWorld's menus, the menus in MaxwellWorld are attached to the left wrist just as a wristwatch would be (for left-handed users, the menu location can be on the right hand). This allows the menus to be removed from the field of view, but keeps them immediately accessible, since users always "knows" where their hands are located. The index finger of the user’s graphically depicted right hand is used to select menu items, and the 3-Ball button is depressed to execute a selection. Executions are confirmed by audible chimes. Navigation in MaxwellWorld is accomplished by selecting the navigation mode, pointing the index finger in the desired direction, and depressing the mouse button.

Using their graphical index finger, students can place both positive and negative charges of various relative magnitudes into the world. Once a charge configuration is established, the force on a positive test charge, electric field lines, potentials, surfaces of equipotential, and lines of electric flux through surfaces can all be instantiated, easily observed, and controlled interactively. For example, the tip of the index finger can be attached to a small, positive test charge, and a force vector associated with the charge depicts both the magnitude and direction of the force of the test charge (and, hence, the electric field) at any point in the workspace. A series of test charges can be "dropped" and used to visualize the nature of the electric field throughout a region.

In a like manner, an electric field line can be attached to one of the charges and to the index finger. A student can then move his or her finger to any point in the workspace and see the field line that connects that point to one of the charges. MaxwellWorld can also display many electric field lines to give students a view of the field produced by a charge configuration. In another mode of operation, the tip of the index finger becomes an electric "potential" meter that, through a simple color map and a "=" or "-" sign on the finger tip, allows students to explore the distribution of potential in the world. Actual values of the potential can be acquired by interrogating a point; digitized speech then provides an audible numerical value.

Via the production of a "Gaussian" surface, the flux of the electric field through that surface can be visually measured. Spherical surfaces (Gaussian or equipotential) can be formed anywhere in the workspace by using the index finger to anchor the center of the sphere and then define the initial radius of the sphere. Upon activation, the surface grows from the selected radius terminus until a closed surface is formed. In the case of equipotential surfaces, the electric forces at any point on the surface can be shown as a color mapped onto the surface at that point. A point on the surface can be "grabbed" to expand or shrink the surface's radius, and its anchor can be moved at will. During all of these activities, the underlying physical simulation updates all physical parameters (force, field lines, and potential).

Description of PaulingWorld

The most recently-developed virtual environment—PaulingWorld—has been created to serve as both a teaching and a "research" tool. This virtual environment was initially built by a single person over six weeks, using our software development tools and deriving its basic structure and interaction metaphors directly from MaxwellWorld. PaulingWorld allows one to examine the structure of both small and large molecules from any viewpoint and in a number of single or mixed representations. One moves between representations by using the same menu approach that MaxwellWorld provides. Molecules can be represented in the familiar ball-and-stick form, as vanderWaals' spheres, as a "wireframe" backbone, as coded sticks, and as icons that replace repetitive structures.

In the latter case, the icons can be interrogated by selecting them with the index finger and depressing the mouse button. The icon is then replaced by a complete representation. Thus, the macrostructure of the molecule remains "iconic," while the region of interest is depicted in a representation of choice. In the ball-and-stick and the sphere representations, texture maps are used to give a visual cue for each atom type (e.g., carbon atoms have with a charcoal-like texture).

To support the rapid examination of various molecules, structural data can be read in directly from pdb (protein database) files that are widely available on the WorldWide Web, allowing a new molecule of interest to be built in a few minutes. Future extensions planned for PaulingWorld include the display of equipotential surfaces (implemented as in MaxwellWorld) and the provision for interactively exploring the effects of atom removal and substitution through direct links to molecular modeling applications.

Assessment of Learning in ScienceSpace

We have developed elaborate assessment methodologies for evaluating the usability and learnability of our ScienceSpace Worlds (Salzman, Dede, & Loftin, 1995):

NewtonWorld Evaluations

Usability: In the summer of 1994, we examined an early version of NewtonWorld, which contained no sound or tactile cues and no visual cues representing energy or velocity. This version provided only two points of reference: the ball and a movable camera. Additionally, a Gamebar for accessing menu items was displayed at all times in the upper right field of view in the head-mounted display (HMD).

We compared interaction alternatives, determined whether users could perform typical tasks with relative ease, assessed the overall metaphor used in NewtonWorld, and examined the general structure of learning activities. We modeled these evaluations after a usability test, asking a small, diverse set of students to perform a series of "typical" activities and provide feedback about their experiences. Nine high school students, five females and four males, participated in this study; two of these students served as pilot subjects. Participants had a range of science, computer and video experience to ensure that our sample was representative.

All students used four variations of the user interface: menu-based, gesture-based, voice-based, and multimodal. On each version, students performed activities such as becoming a ball, using the menus, selecting masses of the balls they were to launch (throw), launching balls, catching balls, and changing camera views. We collected the following data to diagnose usability problems with the user interface: task completion, error frequency, subjective ratings of how easy or difficult students found each task, rankings of the four interaction styles, comments of students, and experimenter observations. We made a number of modifications to the early design of NewtonWorld based on this feedback.

Educators' Design Ideas: At the 1994 Summer Meeting of the American Association of Physics Teachers, we surveyed 107 physics educators and researchers who used NewtonWorld. At this stage of development, NewtonWorld was similar to its current form, except that the Gamebar was displayed on the HMD continuously. Participants observed a 10 minute demonstration of NewtonWorld via a computer monitor, then received a personal demonstration while immersed in the virtual learning environment. After the demonstration, they completed a survey that focused on their interactive experiences, recommendations for improving the system, and perceptions of how effective this 3-D learning environment would be for demonstrating Newtonian physics and conservation laws.

A large majority of participants felt that NewtonWorld would be an effective tool for demonstrating Newtonian physics and dynamics. They found the basic activities, including navigation, easy to perform. These educators were enthusiastic about the three-dimensional nature of this learning environment and appreciated the ability to observe phenomena from a variety of viewpoints. Like students in the early usability tests, many participants experienced difficulty using the menus; several participants also felt a broader field of view would have improved their experiences. Many users had difficulty focusing the optics of the head-mounted display; and several educators expressed concerns regarding the limitations of the prototype and encouraged expanding the activities, environmental controls, and sensory cues provided.

Learnability*:* From December 1994 through May 1995, we conducted formative learnability evaluations on NewtonWorld, focusing on both the importance of the multisensory experience and reference frame usage in learning. Thirty high school students with at least one year of high school physics participated. Each trial required 2 1/2 to 3 hours; learning tasks in the VR required 1 to 1-1/4 hours. During the sessions, students thought aloud as they performed learning tasks that focused on relationships among force, mass, velocity, momentum, acceleration, and energy during and between collisions. For each task, students began by predicting what the relationships or behaviors would be, then experienced them, and finally assessed their predictions based on what they observed. To assess the utility of the multisensory experience, we formed three groups of subjects differentiated by controlling the visual, tactile, and auditory cues that students received while performing learning tasks: 1) visual cues only; 2) visual and auditory cues; or 3) visual, auditory, and haptic cues.

Our observations during the sessions, students' predictions and comments, usability questionnaires, interview feedback, and pre- and post-test knowledge assessments are helping us to determine whether this "first generation" version of NewtonWorld aided students in better understanding relationships among force, motion, velocity, and energy. Single session usage of NewtonWorld was not enough to dramatically improve users' mental models. However, most students found the activities interesting and enjoyed their learning experience. Additionally, many users stated that they felt NewtonWorld provided a good way to explore physics concepts. When asked to list the features they liked most, almost all students cited the ability to beam to various cameras and to navigate in the movable camera. As positive aspects of NewtonWorld, students also cited multisensory informational cues used to represent velocity, energy and collisions, as well as feedback cues.

Students did appear to be more engaged in activities when more multisensory cues were provided. In fact, students receiving sound or sound plus haptic cues rated NewtonWorld as easier to use and the egocentric reference frame as more meaningful than those receiving visual cues only. Useful ideas about the design of these multisensory cues emerged. For example, students who received haptic cues in addition to sound and visual cues performed slightly better than students in other groups on questions relating to velocity and acceleration. Additionally, lesson administrators observed that students receiving haptic and sound cues were more attentive to these factors than students without these cues. However, those same students performed slightly worse on predicting the behavior of the system. One possible explanation is that haptic cues may have caused students to attend more to factors at play just before, during, and after collisions—and less to the motions of the balls.

Overall, the students found the environment easy to use. Nevertheless, students suggested that we could improve the learning experience by expanding the features and representations used in NewtonWorld, and by adding more variety to the nature of the learning activities. Also, as in earlier tests, several users experienced difficulty with eye strain, navigating, and selecting menu items; such problems significantly interfered with the learning task. Based on this feedback, we are modifying the interface and activities in NewtonWorld to enhance its learning outcomes.

Based on these outcomes, we are reconceptualizing NewtonWorld to shift the emphasis of educational activities. Our analysis of the learnability data suggests that younger users might gain more from virtual experiences in sensorily immersive Newtonian environments than do high school students. Via virtual reality experiences, early interventions that undercut these Aristotelian mental models might become a foundation for a less difficult, accelerated transition to a Newtonian paradigm.

<u>MaxwellWorld Evaluation</u>

Usability and Learnability: Throughout the summer of 1995, we have been evaluating MaxwellWorld as a tool for 1) remediating misconceptions about electric fields and 2) teaching concepts with which students are unfamiliar. During the sessions, we have administered one to three lessons centering on the construction and exploration of electric fields (electric force, superposition, test charges, and field lines), learning experiences about electric potential (potential and kinetic energy, potential difference, work, and potential vs. force), and the concept of flux through surfaces (open and closed), leading up to Gauss's Law.

Although these evaluations are still underway, we can report preliminary findings based on 14 high school students (and 4 college students) who have participated in the evaluations thus far. Thirteen of the 14 high school students recently completed their senior year; 1 student recently completed his junior year. All students have completed 1 course in high school physics. Each session lasted for approximately 2 hours. Students were scheduled on consecutive days for the first two sessions, while the third session was conducted approximately 2 weeks later; thus provided a measure of the retention of material over time.

All of the students who were post-tested enjoyed learning about electric fields in MaxwellWorld. When asked about their general reactions to MaxwellWorld, a majority of the students commented that they felt it was a more effective way to learn about electric fields than either textbooks or lectures. Students cited the 3-D representations, the interactivity, the ability to navigate to multiple perspectives, and the use of color as characteristics of MaxwellWorld that were important to their learning experience.

Pre- and post-lesson evaluations show that students had a more in-depth understanding of the distribution of forces in an electric field, as well as representations such as test charge traces and field lines. Manipulating the field in 3-D appeared to play an important role in their learning. For example, several students who were unable to describe the distribution of forces in any electric field prior to using MaxwellWorld gave clear descriptions during the post-test interviews and demonstrations. Also. manipulating field lines and traces in three-dimensions appeared to help students visualize the distribution of force. As an illustration, one student expected field lines to radiate from a single charge along a flat plane and was surprised to see that they radiated in three dimensions. Another student expected to see crossing field lines, but discovered that they could not cross.

Although MaxwellWorld helped students qualitatively understand 3-D superposition, students had difficulty applying superposition when solving post-test problems. Students appeared to understand the concept of superposition during the lessons and particularly enjoyed the demonstrations of superposition (moving the source charges dynamically changes the traces and field lines), often alluding to this during the post-testing. However, many of them exhibited difficulties in applying superposition to post-test demonstrations and sketches.

Through MaxwellWorld, expanding traditional representations to include 1) the third dimension; 2) the ability to manipulate representations; and 3) two color schemes to measure and distinguish the magnitude of the force on and the potential experienced by test charges, field lines, and equipotential surfaces has helped students deepen their understanding of physics concepts. The post-test outcomes and learners' progress through the lessons both showed that students were able to learn about flux through open and closed surfaces using MaxwellWorld. All students performed very well during post-testing, demonstrating an understanding of important and difficult-to-master concepts such as Gauss's law, field vs. flux, and directional flux.

Although only four of these students thus far have used MaxwellWorld to learn about electric potential, all of those students demonstrated that they could visualize the distribution of potential for basic charge arrangements, interpret the meaning of a distribution of potential, identify and interpret equipotential surfaces, relate potential difference and work, and describe some of the differences between electric force and electric potential. All were particularly surprised by 1) the 3-D representations of the equipotential surfaces, particularly in the case of a bipole (two charges of the same size and magnitude), and 2) the fact that forces measured over an equipotential surface were not constant.

We observed significant individual differences in the students' abilities to work in the 3-D environment and with 3-D controls, as well as their susceptibility to symptoms of simulator sickness (eye strain, headaches, dizziness, and nausea). While some students learned to use the menus, manipulate objects, and navigate very rapidly, others required guidance throughout the sessions. Most students experienced nothing more than slight eyestrain; however, two students experienced moderate dizziness and slight nausea during the first session, and, consequently, did not return for the second session. No student complained of any symptoms during the first 30-45 minutes of the lesson, reinforcing our strategy of using multiple, short learning experiences.

Our observations during the sessions, students' predictions and comments, usability questionnaires, interview feedback, and pre- and post-test knowledge assessments are helping us determine whether MaxwellWorld aided students to remediate any of their pre-existing misconceptions and to learn concepts with which they are unfamiliar. Additionally, these experiences are aiding us in developing evolutionary modifications to MaxwellWorld to enhance the learning outcomes obtained.

Lessons Learned from Our ScienceSpace Work

We are developing design heuristics, assessment methodologies, and insights about multisensory learning generalizable to a wide range of educational environments.

Design Heuristics

From the beginning of this project, workers in Houston and Virginia have collaborated on both the design and development of the worlds that comprise ScienceSpace. This initially took the form of teleconferences and the sharing of conceptual drawings via facsimile transmission. Today, developers at each site can view visual displays at both sites and readily exchange software. To minimize the need for duplicative skills at both sites, the Houston team maintains configuration control of the executable software and can troubleshoot problems that arise in "real" time using a combination of Internet and the telephone. This project has made very rapid progress due to this collaboration approach and to the ability to obtain almost immediate feedback when changes, refinements, and additions are made to a given virtual world. The most critical lesson learned in this development is value of a development team composed of a individuals with a wide range of education, experience, and creative energy. Among team members are engineers, psychologists, computer scientists, precollege teachers and students, a former architect, and an artist.

Our research suggests that multisensory immersion for learning depends on actional and symbolic and sensory factors. Inducing actional immersion involves empowering the participant in a virtual environment to initiate actions that have novel, intriguing consequences. For example, when a baby is learning to walk, the degree of concentration this activity creates in the child is extraordinary. Discovering new capabilities to shape one's environment is highly motivating and sharply focuses attention.

In contrast, inducing a participant's symbolic immersion involves triggering powerful semantic associations via the content of a virtual environment. As an illustration, reading a horror novel at midnight in a strange house builds a mounting sense of terror, even though one's physical context is unchanging and rationally safe. Invoking intellectual, emotional, and normative archetypes deepens one's virtual experience by imposing an complex overlay of associative mental models.

Adding stereoscopic images, highly directional and realistic sound, tactile force-feedback, a visual field even wider than IMAX, and the ability to interact with the virtual world through natural physical actions produces a profound sensation of "being there," as opposed to watching. Because common sense responses to physical stimuli work in artificial realities, the learner quickly develops feelings of mastery, rather than the helplessness and frustration that are typical when first attempting to use an unfamiliar computer interface or operating system.

We are finding that new theories of instructional design are needed to develop worlds based on these heuristics. Standard approaches to building 2-D microworlds (graphical user interfaces, activities based around a planar context) fail badly when scaled to developing 3-D experiences. Multimodal interaction with multisensory output adds additional degrees of complexity. However, we are shortening our development process as we evolve design heuristics, tools, interfaces, and peripherals uniquely based around virtual reality.

Assessment Techniques and Protocols

Conventional human subjects protocols are inadequate for assessing the usability and learnability of virtual worlds. Although infrequent, potential side effects such as “simulator sickness” mandate the inclusion of special questions and protections to ensure users’ comfort. Moreover, because each person evolves a unique psychomotor approach to interacting with the physical context, individuals have much more varied responses to 3-D, multimodal interfaces than to the standard 2-D graphical user interface with menus, windows, and mouse. As a result, portions of our protocols must center on calibrating and customizing the virtual world’s interface to that particular learner. Also, evaluating the multisensory dimensions of an immersive virtual world adds an additional dimension of complexity to the assessment process.

We have developed extensive assessment methodologies and instruments, literally hundreds of pages in length, for studying the worlds we have created. In addition, we are videotaping the hours of time we spend with each subject, then studying these records for additional insights. This careful evaluation strategy is generating detailed data from which we are gaining a comprehensive picture of how multisensory immersion can enhance learning, as well as how virtual reality’s usability can be enhanced. Beyond our own work, the strategies underlying these assessment methodologies and instruments are generalizable to a wide range of synthetic environments and virtual worlds and thus are an important product of this project.

Challenges in Using Current Virtual Reality Interfaces

We have identified the following usability issues characteristic of virtual reality interfaces:

¥ Students exhibit noticeable individual differences in their interaction styles, abilities to interact with the 3-D environment, and susceptibility to simulator sickness.

¥ Immersion does present some challenges for lesson administration (for example, students in the head-mounted display are not able to access written instructions or to complete written questions.) We have found that verbal interaction works well.

¥ Limitations of the physical design and optics in today's head-mounted displays may cause discomfort for users. Since the visual display is an integral part of interaction and communication of information in these learning environments, these limitations are a current hindrance to usability and learning.

¥ Spreading lessons over multiple VR sessions appears to be more effective than covering many topics in a single session. While students began to challenge their misconceptions during a single 3-hour NewtonWorld session, many had trouble synthesizing their learning during post-testing. We believe that factors such as fatigue and cognitive overhead in mastering the interface influenced these outcomes. In contrast, our MaxwellWorld evaluations were completed over multiple sessions, tackling fewer topics during each session, and dedicating less time per session to pre- or post-testing. Reviews and post-tests demonstrated that students were better able to retain and integrate information over multiple lessons.

In our judgment, none of these issues precludes developing compelling learning experiences in virtual reality.

Insights about Learning and Knowledge Representation

As discussed later, our goal is to develop an overarching theory of how learning difficult, abstract material can be strongly enhanced by multisensory “immersion” (based on 3-D representations; multiple perspectives and frames of reference; a multimodal interface; simultaneous visual, auditory, and haptic feedback; and types of interaction unavailable in the real world). Illustrative themes applicable across all the virtual worlds we have created are listed below.

¥ Multisensory cues can engage learners, direct their attention to important behaviors and relationships, help students better understand different sensory perspectives, prevent interaction errors through feedback cues, and enhance perceived ease of use.

¥ The introduction of new representations and perspectives can help students gain insights for remediating misconceptions formed through traditional instruction (e.g., many representations used by physicists are misleading for learners), as well as aiding learners in developing correct mental models. Our research indicates that qualitative representations (e.g., shadows showing kinetic energy in NewtonWorld, colors showing the magnitude of a force or energy in MaxwellWorld) increase saliency for crucial features of both phenomena and traditional representations.

¥ Allowing multimodal interaction (voice commands, gestures, menus, virtual controls, and physical controls) facilitates usability and seems to enhance learning. Multimodal commands offer flexibility to individuals, allowing them to adapt the interaction to their own interaction preferences and to distribute attention when performing learning activities. For example, some learners prefer to use voice commands so that they need not redirect their attention from the phenomena of interest to a menu system. (However, if virtual worlds are designed for collaborative learning, voice may be a less desirable alternative.)

¥ Initial experiences in working with students and teachers in MaxwellWorld suggest collaborative learning may be achievable by having two or more students working together and taking turns "guiding the interaction," "recording observations," and "experiencing activities" in the virtual reality. Extending this to collaboration among multiple learners co-located in a shared synthetic environment may further augment learning outcomes.

¥ In general, usability of the virtual environment appears to enhance learning. However, optimizing the interface for usability does not necessarily optimize for learning. We have found instances in which changes to make the user interface more usable may actually impede learning. For example, in NewtonWorld to use size as an indication of a ball’s mass is facile for learners, but would reinforce a misconception that mass correlates with volume.

Our goal is to develop an overarching theory of how learning difficult, abstract material can be strongly enhanced by multisensory “immersion” (based on 3-D representations; multiple perspectives and frames of reference; a multimodal interface; simultaneous visual, auditory, and haptic feedback; and types of interaction unavailable in the real world).

The Evolution of ScienceSpace

The next stage of our ScienceSpace research will focus on optimizing, evaluating, and translating from laboratory to classroom settings the immersive environments we have created. Beyond assessing the educational utility of these particular virtual worlds, the major underlying theme is developing new insights about learning based on multisensory immersion, intelligent coaching, motivation in synthetic environments, and collaboration among students.

Enhancements to All Three Worlds

Through our usability and learnability studies, we have developed a set of design enhancements for each of our virtual worlds. Space limitations preclude listing the detailed capabilities we plan to add to each. In all our worlds, we plan to experiment with collaborative learning among geographically remote users inhabiting a shared virtual context. Collaboration among users' "avatars" in shared synthetic environments enables a wider range of pedagogical strategies (e.g., peer teaching, tutoring, apprenticeship) and may make VR environments more intriguing to students who are most motivated to learn when intellectual content is contextualized in a social setting.

We will soon have identical VR systems available to allow local sharing via campus Ethernet or even ATM-level interconnectivity. Via a dedicated ISDN telephone line, we can implement shared worlds through links between Texas and Virginia, using technology similar to that developed by NASA to train astronauts in Houston and Germany to train in the same virtual environment. Important questions to be answered are the value of providing learners with graphically-generated bodies and the degree to which the fidelity of the graphical representation affects learning and interaction (here fidelity is not simply visual fidelity, but also the matching of real body motions to the animation of the graphical body).

We will also investigate the effectiveness of group learning situations in which three students rotate roles among (1) using the headmounted display, (2) serving as external guide, and (3) participating as a reflective observer. This provides a means of minimizing eyestrain and fatigue from usage of the virtual reality system while still enabling substantial time on task. However, virtual reality systems do present unique design challenges in facilitating such face-to-face learner collaboration because of the intrusive nature of the head-mounted display. At Houston we will soon have an immersive "CAVE"—a cube, ten-feet on a side, that provides for sensory immersion without the use of an HMD and permits several users to be in the same virtual reality simultaneously without the need for gear that isolates each user.

Another type of enhancement we plan to introduce into all our virtual worlds is the incorporation of "intelligent" coaching. One of the authors has extensive experience in the development of intelligent tutoring and coaching systems, including an ITS to enhance physics education in high schools (Loftin et al, 1991; 1992), which has now been licensed for commercial distribution. Some of the cues and feedback now provided by human agents external to our virtual worlds could, through artificial intelligence techniques, be embedded into the VR environment on a stand-alone basis. Such a guide might even appear to the user as a synthetic figure with a limited, but useful repertoire of emotions; the funded project we are beginning for the Office of Naval Research provides a strong foundation [via the Jack system from Dr. Norm Badler (1995) at the University of Pennsylvania] to develop such an affective capability for ScienceSpace environments. In conjunction with peer tutoring, this intelligent coaching could make VR environments more practical in real-world learning settings by reducing the need for an expert teacher to serve as a constant guide.

In all three worlds, we also plan to add additional representations (e.g., graphical output in a "scoreboard" format) that will facilitate learners' bridging from qualitative experiences to quantitative mathematical formalisms. In addition, we plan to introduce game-like elements to provide enhanced motivation. Experiences similar to laboratory experiments are unlikely to involve young students or learners initially uninterested in science. In NewtonWorld, for example, bouncing, colliding balls form a natural substrate for several types of games that could enhance motivation and concentration through fantasy, curiosity, challenge, competition, and cooperation (Malone & Lepper, 1985).

Finally, we intend to contrast learning outcomes in all three worlds to comparable experiences with other pedagogical strategies (2-D microworlds, texts, and lecture/discussion sessions). For NewtonWorld, White and Frederickson's Thinkertools microworld (1993) provides one possible framework for such a comparison, as do Trowbridge and Sherwood's EMField microworld (1994) and the simulations of electrostatic phenomena in 2-D that are currently used by our colleague Dr. Joe Redish at the University of Maryland.. Such studies should help to clarify when sensorily immersive experiences deliver significantly enhanced learning beyond less elaborate alternative teaching methods. Through follow-on research with selected subjects over a period of years, we can also determine the extent to which multisensory immersion facilitates generalization, transfer, and retention.

Transfer to Classroom Settings

We plan to develop scaled-down versions of our ScienceSpace worlds on high-end conventional desktop machines (e.g., PowerPC or Intel-based personal computers). Such platforms are more affordable and maintainable by schools than the exotic graphics supercomputers now required to get the capabilities we need. Given current rates of progress in graphics processors that perform texture mapping at high pixel fill rates and the approaching availability of plug-in boards based on these chips,, we expect that, in 2-1/2 years, we can configure for about $20,000 a desktop system that can deliver a somewhat limited subset of our three virtual worlds.

We intend to deploy several such systems in typical classrooms to study:

- what proportion of students' learning on sophisticated VR systems can be duplicated with a more limited range of capabilities;
- what balance of lecture, readings, discussion, 2-D microworlds, physical manipulatives, and sensory immersion seems appropriate for mastering difficult and abstract content;
- how the mathematics curriculum can be utilized to bridge between qualitative VR experiences and quantitative, symbolic representations;
- how students and teachers develop and extend their learning experiences when given access to virtual reality systems and authoring tools; and
- challenges and difficulties teachers face in integrating these types of devices and content into conventional curriculum and classroom structures.

Such an implementation strategy would build a foundation for transposing our research from laboratory studies to robust, practical implementations. Thinking now about eventual deployment and dissemination is vital. Due to the huge profits of the videogame market and the entertainment industry, we expect that in less than a decade many of the capabilities of our expensive laboratory equipment will be "under the Christmas tree" for families, including impoverished households and homes in rural areas.

Conclusion

An overarching theme in all our ScienceSpace research is to develop a theory of how multisensory "immersion" aids learning. In our virtual worlds, we can simultaneously provide learners with 3-D representations; multiple perspectives/frames of reference; a multimodal interface; simultaneous visual, auditory, and haptic feedback; and types of interaction unavailable in the real world (e.g., seeing through objects, flying like Superman). With careful design, these capabilities all can synthesize to create a profound sense of motivation and concentration conducive to mastering complex, abstract material. Studying this new type of learning experience to chart its strengths and its limits is an important frontier for cognitive science research and constructivist pedagogy.

Acknowledgments

This work is supported by NSF's Applications of Advanced Technology Program, Grant RED-9353320, and by NASA through a grant (NAG 9-713) and through access to equipment and computer software. The authors gratefully acknowledge the aid of Kim Adams, Craig Calhoun, Wayne Herbert, Belinda Hyde, Jeff Hoblit, Pat Hyde, Deirdre McGlynn, Mason Menninger, Kevin Pong, and Saba Rofchaei.

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