Using Virtual Reality Technology to Convey Abstract Scientific Concepts

Final Draft

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

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

R. Bowen Loftin
Virtual Environment Technology Lab
University of Houston
Houston, TX 77023
(713) 743-1006
bowen@uh.edu

Katy Ash
Department of Psychology
George Mason University
Fairfax, VA 22030
(703) 426-9050
kash@gmu.edu

"The simple fact is that the world of sensory experience is not Newtonian. More than a little research shows that children and adults learn many things about the physical world through their experience, but do not learn about Newton's Laws. In a deep sense, physics is not about the world as we naturally perceive it, but about abstractions that have been put together with effort over hundreds of years, which happen to be very powerful when we learn to interpret the world in their terms... The trick is not to turn experience into abstractions with a computer, but to turn abstractions like laws of physics into experiences. Science is reorganized intuition." Andrea diSessa [1986].

Imagine launching and catching balls in an environment with neither gravity nor friction. Imagine creating and altering electrostatic fields, releasing charged particles to be propelled through those fields. Imagine manipulating atoms and observing the forces created when molecules bond. Then, as a giant step further, imagine being able to directly experience these phenomena by becoming a part of them "inside" a virtual world: being a ball as it bounces, riding on a test charge as it moves through an electrostatic field, becoming an atom as it bonds. These are the kinds of learning activities enabled in the virtual worlds of ScienceSpace. Our research suggests that such immersive, multisensory experiences enhance students' abilities to conceptualize and integrate complex, abstract scientific ideas.

Many groups are developing sophisticated instructional designs with well-understood, conventional technologies, such as today's personal computing and telecommunications devices. In contrast, our work explores the strengths and limits for learning of a very powerful emerging technology, virtual reality (VR). However, Project ScienceSpace does not focus solely on developing educational worlds using an interface that enables multisensory immersion. In addition, our studies are exploring new ideas about the nature of learning based on the unique capabilities for research that virtual reality provides. ScienceSpace worlds enable unique, extraordinary educational experiences that help learners challenge their intuitions and construct new understandings of science. Our evaluations are designed to examine various aspects of this learning experience, process, and outcomes. Sophisticated experimentation along these dimensions is critical to determining the educational potential of three-dimensional, sensorily immersive virtual environments, a medium that the entertainment industry will place "under the Christmas tree" within the next decade.

One of the challenges in working with instructional media is that developers and educators are confronted with a rapidly moving target in terms of information technology's capabilities. The business and entertainment sectors are driving a fast-paced evolution of the devices people have in their workplaces and homes. Researchers and educators are scrambling to assess the potential, develop pedagogical strategies, create instructional materials, and implement a school-based infrastructure for today's technologies—only to find that computers and communications are "morphing" into new media of even greater power. Not since the dawn of the industrial revolution has the workplace and society students will confront as adults been so different from what their parents face today. For educational tools to fall behind the pace of technological advance is to sell out a generation of learners, so charting the strengths and limits of emerging media for learning is imperative.

In particular, people's understanding of what computers can do has shifted dramatically as the size and cost of these devices has decreased while their power has grown. First, computers were seen as number-crunching machines, then came data processing, now we live in the age of tools to manipulate symbols and information. Our VR research is based on the growing certainty that the next evolutionary stage is computers and telecommunications fusing into virtual environments. "Cyberspace" is not simply a channel down which content can flow, but a virtual place to live that (for better or for worse) competes directly with reality for the attention of many, especially this generation of students. For this reason, charting the strengths and limits of virtual reality, long before it is ubiquitous in the form of videogames, is vital for educational technology as a field.

To help in understanding the advanced learning tools we are developing, this chapter begins with a brief introduction to our worlds and to the virtual reality technology upon which they are built. We then describe our learner-centered strategy for design and evaluation and identify issues that have shaped the development and assessment of our immersive, multisensory environments. Next, we discuss the evolution and evaluation of each ScienceSpace world. Finally, we describe insights gained both about learning and about emerging educational technologies such as virtual reality, then delineate our plans for future research.

ScienceSpace Worlds

ScienceSpace consists of three worlds in various stages of development: NewtonWorld (NW), MaxwellWorld (MW), and PaulingWorld (PW). In NewtonWorld, users experience laws of motion from multiple points of view. In this world with neither gravity nor friction, balls hover above the ground. Users can become a ball; see, hear, and feel its collisions; and experience the ensuing motion (see Figure 1). In MaxwellWorld, users build electrostatic fields and manipulate multiple representations of force and energy. They can directly experience the field by becoming a test charge that is propelled by the forces of the electric field (see Figure 2). In PaulingWorld, users learn about molecular structure and chemical bonding. They can explore the atoms and bonds of a simple molecule such as water and can manipulate the amino acids of complex proteins such as hemoglobin (see Figure 3).

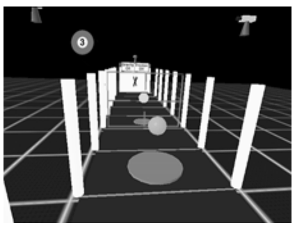

Figure 1. Balls in NW

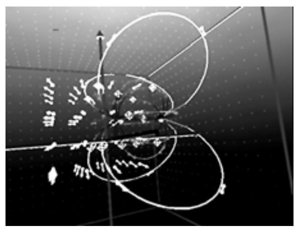

Figure 2. A dipole in MW.

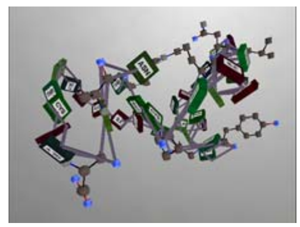

Figure 3. A molecule in PW.

The interface of our immersive, multisensory environments is typical of current high-end virtual reality. ScienceSpace’s hardware architecture includes a Silicon Graphics Onyx Reality Engine2 4-processor graphics workstation, Polhemus magnetic tracking systems utilizing a stylus or 3Ball (a three-dimensional mouse), and a Virtual Research VR4 head-mounted display (HMD). Sound is produced by a Silicon Graphics Indy workstation and is experienced via HMD headphones and external speakers. Vibrations are delivered to a subject's torso using a "vest" with embedded subwoofers. This interface enables us to immerse students in 3-D virtual worlds using the visual, auditory, and haptic (touch and pressure) senses.

The software interface relies on 3-D models and qualitative representations controlled through NASA-developed physical simulation applications. Visual models are 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 (VR-Tool) that displays the virtual worlds while connecting them to underlying physical simulations. User 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.

Students use a virtual hand (controlled by the 3Ball), menus, and direct manipulation to perform tasks in these immersive virtual environments. One Polhemus tracker is in the 3Ball held by the participant in one hand, a second is mounted on a fixture and held in the other hand, and a third is mounted on the HMD. The user's hand holding the 3Ball or stylus is represented in the virtual world as a hand with the index finger extended, aligned with the user's hand. The menu system is attached to the tracker held by the other hand. Displaying the menu in this manner allows students to remove the menu from their field of view, while keeping it immediately accessible.

Students select menu items by holding up the menu with one hand, pointing to the menu option with the virtual hand, and depressing the 3Ball button. Thus, menu selection in our ScienceSpace worlds is similar to menu selection on two-dimensional interfaces in which users manipulate the menu with a cursor controlled by a mouse. Figure 4 shows a student immersed in one of ScienceSpace's worlds. She is using the 3Ball and tracker to control a virtual hand and menu system.

Figure 4. A student immersed in ScienceSpace.

Our worlds also utilize direct manipulation, empowering students to interact with objects in the space. For example, MaxwellWorld enables learners to place source charges in a 3-D space, to move them around, and to delete them. In NewtonWorld, students can "beam" (teleport) among cameras located in various frames of reference and can launch and catch balls. Learners in PaulingWorld can grasp and rotate molecular structures. Also, users can change their location (“fly”) by selecting the navigation mode on the menu, pointing the virtual hand in the desired direction, and depressing the 3Ball button.

Our Approach

Throughout the development of our ScienceSpace worlds, we have employed a learner-centered design strategy that focuses simultaneously on interface issues, users’ subjective experiences in virtual reality, and learning outcomes [Soloway, Guzdial, & Hay, 1994; Salzman, Dede, & Loftin, 1995]. The issues and strategies underlying this learner-centered design and evaluation approach are generalizable to a wide range of synthetic environments beyond virtual reality.

When working with each of our worlds, we establish learning objectives and design goals through a careful initial analysis of (1) what students need to enable their learning (including the types of experiences that might aid in mastering the complexities of the particular scientific domain) and (2) the capabilities and limits of virtual reality technology (the role multisensory immersion in three-dimensional virtual environments could play in meeting these learner needs). We then proceed through iterative cycles of design and evaluation. Four issues are critical to our evaluations:

- *The learning experience.* The VR experience can be characterized along several dimensions. We have focused on participants’ subjective judgments of usability, simulator sickness, immersion, meaningfulness of our models and representations, and motivation. In designing our evaluations, we not only assess usability, but we also attempt to minimize usability problems through calibration of our equipment to each individual participant’s idiosyncratic strategy for interacting with three-dimensional space. For example, portions of our protocols center on customizing the virtual world’s interface to that particular learner’s visual perception. We also measure simulator sickness in order to ensure users’ comfort. The remaining measures—immersion, meaningfulness of our models and representations, and motivation—are designed to yield further insights into which factors provide greatest leverage for learning.

- *Learning.* We are interested in both the learning process and in learning outcomes. Throughout the learning process, we monitor how students are progressing through activities within the virtual environment. Asking students to make verbal predictions about a certain activity, to describe what they observe when performing the activity, and to compare their predictions to their observations had been a useful way to monitor the learning process [White. 1993]. As discussed in detail later, to assess learning outcomes we examine mastery of concepts at both the “descriptive” and the “causal” levels using multiple measures (e.g., conceptual, two-dimensional, and three-dimensional understanding).

- *The learning experience vs. learning.* Our focus in this contrast is to understand the relationship between the virtual reality experience and learning and to identify when the VR experiences helps or hinders learning. For example, increased student motivation may aid learning, while simulator sickness may reduce educational gains.
- *Educational utility:* This contrast centers on whether, for particularly complex and abstract domains, the virtual reality medium is a better (or worse) teaching tool than other pedagogical approaches. We compare the quality and efficiency of learning among different alternatives of varying cost, instructional design, and teaching strategy. In particular, we compare our learning outcomes to less-complex technology-based scientific modeling approaches such as 2-D "microworlds."

We collect information along these four dimensions using a variety of techniques. Throughout sessions with students, we carefully monitor the learning process and log users' comments and reactions. The learning sessions are also videotaped so that we can study these records for additional insights. We use sketches; demonstrations; and assessment instruments based on short answer, open-ended response, true/false, and matching items to capture dimensions of learning. Questionnaires and interviews are used to gather users' perceptions about the learning experience.

With each cycle of evaluation, we add to a pool of knowledge that is helping us to make design decisions and to more fully understand how multisensory immersion can enhance learning. By focusing on the students' experience as well as their learning, we gain insights that guide the refinement of the user interface and aid us in understanding the strengths and limits of VR's capabilities for conveying complex scientific concepts.

An Analysis of How VR technology Might Aid Learning

To understand how to help students master complex scientific concepts, examining the general nature of learning is vital. First, a prerequisite for learning is attention: students must focus on or be engaged in an experience in order for learning to occur. Second, meaningful representations are necessary to communicate information [Hewitt, 1991]. Third, multiple mappings of information can enhance learning [Kozma, Chin, Russell, & Marx, 1997]. Additionally, learning-by-doing and reflective inquiry are both effective in inducing learning; through experience, students can extend and modify their knowledge constructs (mental models) based on discontinuities between expected and actual behaviors of phenomena. In addition, researchers are finding that the social construction of knowledge among students—even when their interactions are mediated by virtual environments—enables innovative, powerful types of collaborative learning [Turkle, 1995; Bruckman & Resnick, 1995].

In particular, mastery of abstract science concepts requires learners to build generic and runnable mental models [Larkin, 1983]. These often must incorporate invisible factors that represent intangible forces and other abstractions [diSessa, 1983]. Frequently, the ability to translate among reference frames is crucial. Unfortunately, learners have trouble identifying important factors or imagining new perspectives [Redish, 1993]. They also lack real-life analogies upon which to build their mental models. For example, in scientific domains such as quantum mechanics, relativity, and molecular bonding, learners cannot draw on personal experiences to provide metaphors for these phenomena.

Additionally, real-life experiences (which are confounded with invisible factors) often distort or contradict the principles students need to master. For example, the universal presence of friction makes objects in motion seem to slow and stop "on their own," undercutting the face validity of Newton's First Law. As a result, most learners—including many science majors—have difficulty understanding science concepts and models at the qualitative level, let alone the problems that occur with quantitative formulation [Reif & Larkin, 1991]. These misconceptions, based on a lifetime of experience, are very difficult to remediate with instructionist pedagogical strategies.

Substantial research indicates that traditional lectures and laboratory sessions are not adequate for teaching difficult science concepts. For example, researchers in physics education have demonstrated that students typically enter and leave high school and college level physics courses with faulty mental models [Halloun & Hestenes, 1985a]. Some of these misconceptions may have little effect on learners' understanding of science or their ability to cope with everyday phenomena; but the cumulative effect of large numbers of misconceptions may undermine students' comprehension.

Based on this analysis, we believe that, to master complex scientific concepts, pedagogical tools and strategies should (1) provide learners with experiential metaphors and analogies to aid in understanding abstractions remote or contradictory to their everyday experience and (2) enable students to participate in shared virtual contexts within which the meaning of this experience is socially constructed. To date, uses of information technology to apply these pedagogical principles have centered on creating computational tools and two-dimensional virtual representations that students can manipulate to complement their memory and intelligence in constructing more accurate mental models. Perkins [1991] classifies types of "constructivist" paraphernalia instantiated via information technology: information banks, symbol pads, construction kits, phenomenaria, and task managers. Transitional objects (such as Logo's "turtle") are used to facilitate translating personal experience into abstract symbols [Papert, 1988; Fosnot, 1992]. Thus, technology-enhanced constructivist learning currently focuses on how representations and tools can be used to mediate interactions among learners and natural or social phenomena.

Virtual realities for guided inquiry have the potential to complement existing approaches to science instruction [Dede, 1995]. VR has several characteristics that make it promising as a constructivist tool for learning science via students' manipulation of models:

- *immersion:* Learners develop the subjective impression that they are participating in a "world" comprehensive and realistic enough to induce the willing suspension of disbelief [Heeter, 1992; Witmer & Singer, 1994]. By engaging students in learning activities, immersion may make important concepts and relationships more salient and memorable, helping learners to build more accurate mental models. Also, inside a head-mounted display, the learner's attention is focused on the virtual environment without the distractions presented in many other types of educational environments.
- *multiple three-dimensional representations and frames of reference:* Spatial metaphors can enhance the meaningfulness of data and provide qualitative insights [Erickson, 1993]. Enabling students to interact with spatial representations from various frames of reference may deepen learning by providing different and complementary insights.
- *multisensory cues:* Via high-end VR interfaces, students can interpret visual, auditory and haptic displays to gather information, while using their proprioceptive system to navigate and control objects in the synthetic environment. This potentially deepens learning and recall [Psotka, 1996].
- *motivation:* Learners are intrigued by interactions with well designed immersive "worlds," inducing them to spend more time and concentration on a task [Bricken & Byrne, 1993].
- *telepresence:* Geographically remote learners can experience a simultaneous sense of presence in a shared virtual environment [Loftin, 1997].

Full immersion and telepresence 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 experience in a virtual environment by imposing an complex overlay of associative mental models.

Beyond actional and symbolic immersion, advances in interface technology also enable sensory immersion in virtual realities designed to enhance learning. Inducing a sense of physical immersion within a synthetic context involves manipulating human sensory systems (especially the visual system) to enable the suspension of disbelief that one is surrounded by a virtual environment. The impression is that of being inside an virtual “world” rather than looking through a computer monitor "window" into a synthetic environment: the equivalent of diving rather than riding in a glass-bottomed boat. A weak analog to sensorily immersive interfaces that readers may have experienced is the IMAX motion picture theater, in which a movie projected on a two-story by three-story screen can generate in observers strong sensations of motion. 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.

The multisensory immersion learners experience through virtual reality technology has the potential to complement other, less complex educational tools and strategies. VR makes possible new kinds of learning experiences that are highly perceptual in nature. Via this technology, students can be immersed within a phenomenon visually, auditorily and haptically; and they can experience that phenomenon from multiple, novel frames of reference. These kinds of activities increase the saliency of important factors and relationships and help learners gain experiential intuitions about how the natural world operates. For complex, abstract material difficult to teach in any other manner, virtual reality seems a promising educational medium.

However, despite its strengths, current virtual reality technology has many limits and problems that can potentially interfere with students' mastery of scientific concepts. These include:

- Virtual reality's physical interface is cumbersome [Krueger, 1991]. Head-mounted displays, cables, 3-D mice, and computerized clothing all can interfere with interaction, motivation, and learning.
- Display resolution is inversely proportional to field of view. A corresponding trade-off exists between display complexity and image delay [Piantanida, Boman, & Gille, 1993]. The low resolution of current VR displays limits the

fidelity of the synthetic environment and prevents virtual controls from being clearly labeled.

- VR systems have limited tracking ability with delayed responses [Kalawsky, 1993].
- Providing highly localized 3-D auditory cues is challenging, due to the unique configuration of each person's ears. Also, some users have difficulty localizing 3-D sounds [Wenzel, 1992].
- Haptic feedback is extremely limited and expensive. Typically, only a single type of haptic feedback can be provided by computerized clothing; for example, one glove may provide heat as a sensory signal, but cannot simultaneously provide pressure. In addition, using computerized clothing for output can interfere with accurate input on users' motions.
- Virtual environments require users to switch their attention among the different senses for various tasks [Erickson, 1993]. To walk, users must pay attention to their haptic orientation; to fly, users must ignore their haptic sense and focus on visual cues. Also, as Stuart & Thomas [1991] describe, multisensory inputs can result in unintended sensations (e.g., nausea due to simulator sickness) and unanticipated perceptions (e.g., awareness of virtual motion, but feeling stationary in the real world).
- Users often feel lost in VR environments [Bricken & Byrne, 1993]. Accurately perceiving one's location in the virtual context is essential to both usability and learning.
- The magical (unique to the virtual world) and literal (mirroring reality) features of VR can interact, reducing the usability of the interface [Smith, 1987]. Also, some researchers have demonstrated that realism can detract from rather than enhance learning [Wickens, 1992].

As virtual reality technology evolves, some of the challenges to educational design will recede. At present, however, achieving the potential of immersive, synthetic worlds to enhance learning requires transcending these interface barriers through careful attention to usability issues.

Another class of potential problems with the use of immersive virtual worlds for education is the danger of introducing new or unanticipated misconceptions due to the limited nature of the "magic" possible via this medium. For example, learners will not feel their sense of personal physical weight alter, even when the gravity field in the virtual reality they have created is set to zero. The cognitive dissonance this mismatch creates, due to conflicting sensory signals, may create both physiological problems (e.g., simulator sickness) and possibly false intellectual generalizations. One part of our research is to examine the extent to which manipulating learners' visual, auditory, and tactile cues may induce subtle types of misconceptions about physical phenomena. The medium (virtual reality) should not detract from the message (learning scientific principles).

Designing and Evaluating ScienceSpace

ScienceSpace worlds rely on the 3-D representations; multiple perspectives and frames of reference; multimodal interaction; and simultaneous visual, auditory, and haptic feedback afforded by VR technology. Our design of each of the worlds and the kinds of activities they support is based on a detailed assessment of what learning experiences are required to master complex scientific material. In the following sections, we discuss the design, evaluation, and iterative evolution of our immersive virtual worlds.

MaxwellWorld

MaxwellWorld is designed to help students understand the difficult concepts underlying electrostatic fields (distribution of force & energy). Our early work with students and with our domain expert, Dr. Edward Redish of the University of Maryland, uncovered the following about pupils' learning of electric fields. (Many of these insights also apply to mastering concepts about any type of vector field.) Electric fields and their associated representational formalisms are three-dimensional, abstract, and have few analogies to learners' everyday experience. As a result, students have trouble understanding the relationship of abstractions about electric fields to phenomenological dynamics. Learners also often confuse the concepts of force and energy, indicating that they do not understand the meaning of the representations that are traditionally used (e.g., 2-D field lines, 2-D equipotential lines) to convey information about these abstractions.

In addition, learners have trouble understanding how the electric field would propel a test charge through the field if it were free to move. This is because they lack the ability to visualize the distribution of forces throughout a vector field, to relate how that distribution of force translates into the motion of the test charge, or even to understand the concept of superimposed forces-at-a-distance. This is another example of an instance in which students lack real-life referents that provide metaphors for these behaviors, as well as an experimental environment in which to test and validate their mental models.

Overall, students lack a qualitative understanding of these electric field concepts. Such qualitative mental models are believed to lay the foundation for more scientific, abstract understanding [Reimann & Spada, 1996; White, 1993; White & Frederickson, 1992]. Therefore, we began our design by exploring ways to help students develop generic, qualitative 3-D mental models of these phenomena, models that incorporate intangible, abstract factors such as force and energy.

In the design of MaxwellWorld, we (1) enable learners to virtually experience scientifically accurate models of electric fields; (2) make factors salient that are not perceptible in the real world through multisensory cues (e.g., how the forces at each point in space continually accelerate a test charge); (3) motivate learners by immersing them within the phenomena; and (4) capture and direct learners' attention to relationships between force and energy through enhancing traditional scientific formalisms used by experts, but “cognitively opaque” to novices.

MaxwellWorld allows learners to explore electrostatic forces and fields, learn about the concept of electric potential, explore how test charges would move through the space, and "discover" the nature of electric flux. The fieldspace in this virtual world 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.

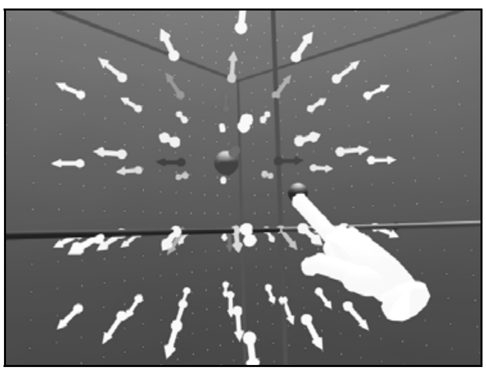

Figure 5. User exploring a field with a test charge.

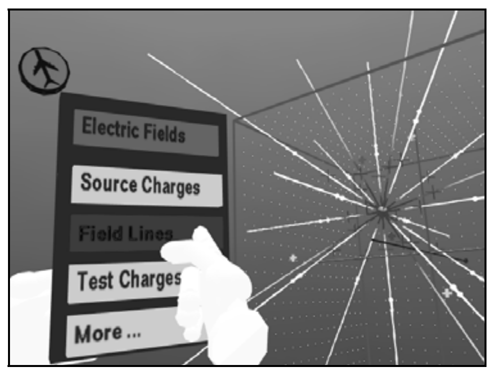

Figure 6. Activating the menu via the virtual hand.

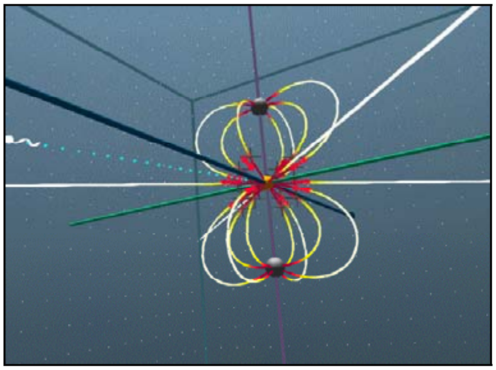

Figure 7. Bipole with moving test charge.

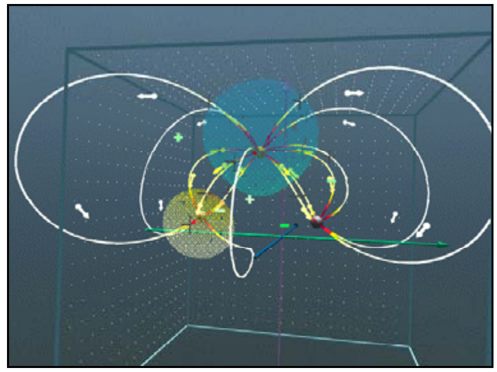

Figure 8. Tripole with equipotential surface.

Students use a virtual hand, a menu, direct manipulation, and navigation to interact with this world (see Figure 5). Learners can place both positive and negative charges of various relative magnitudes into the world. Once a charge configuration is established, users can instantiate, observe, and interactively control 3-D representations of the force on a positive test charge, electric field lines, potentials, surfaces of equipotential, and lines of electric flux through surfaces. For example, a small, positive test charge can be attached to the tip of the virtual hand. A force meter associated with the charge then depicts both the magnitude and direction of the force of the test charge (and, hence, the electric field) at any point in the workspace (see Figure 6). A series of test charges can be "dropped" and used to visualize the nature of the electric field throughout a region. In our most recent version of MaxwellWorld, learners can first release a test charge and watch its dynamics as it moves through the fieldspace (see Figure 7), then “become” the test charge and travel with it as it moves through the electric field.

An electric field line can also be attached to the virtual hand. Learners can then move their hands to any point in the workspace and see the line of force extending through that point. 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 virtual hand 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 fieldspace. Via the production and manipulation of equipotential surfaces, learners can watch how the shapes of these surfaces alter in various portions of the fieldspace (see Figure 8). The surfaces are colored to indicate the magnitude of the potential across the surface; however, the student can also choose to view the electric forces as they vary across the surface. This activity helps students to contrast the concepts of electric force and potential.

Via the production of a "Gaussian" surface, the flux of the electric field through that surface can be visually measured. Gaussian surfaces can be placed anywhere in the workspace by using the virtual hand to anchor the sphere; the radius (small, medium, large) is selected from the menu. This representation enables students to explore flux through a variety of surfaces when placed at various points in the field. All these capabilities combine to enable representing many aspects of the complex scientific models underlying vector field phenomena.

Formative evaluations of MaxwellWorld

During the summer of 1995, we conducted formative evaluations of MW. We examined MaxwellWorld's effectiveness as a tool for learning and remediating misconceptions about electric fields, electric potential, and Gauss's law.

Fourteen high school and 4 college students completed from 1 to 3 lessons in MaxwellWorld. Thirteen of the 14 high school students had recently completed their senior year; 1 student had recently completed his junior year. All students had 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. Below is a brief overview of some of the findings:

- Overall, students felt MaxwellWorld was a more effective way to learn about electric fields than either textbooks or lectures. College level students found that they were better able to visualize and understand electrostatic phenomena. They cited the 3-D representations, interactivity, the ability to navigate to multiple perspectives, and the use of color as characteristics of MaxwellWorld important to their learning experience.
- Pre- and post-lesson evaluations show that, while using MaxwellWorld, students developed an 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 electric field in 3-D appeared to play an important role in students' ability to visualize the distribution of energy and force. 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.
- We observed substantial individual variability in the students' abilities to work in the 3-D environment and with 3-D controls (usability), and their susceptibility to symptoms of simulator sickness (eye strain, headaches,

dizziness, and nausea). Typical usability problems occurred when navigating, using menus, and deleting source charges.

These evaluations showed that lessons in MaxwellWorld helped students 1) learn advanced concepts using MaxwellWorld, and 2) remediate misconceptions. However, they did not allow us to establish whether learning was due to the unique capabilities of MaxwellWorld's multisensory immersion, to the lessons students received, or to instructional capabilities than could be replicated in a less complex 2-D microworld.

Comparative evaluations of MaxwellWorld

In January, 1996, we initiated an extended study designed to compare learning and usability outcomes from MaxwellWorld to those from a highly regarded and widely used two-dimensional microworld, EM Field™, which covers similar material [Dede, Salzman, Loftin & Sprague; accepted for publication]. Stage one of this study compared MaxwellWorld (MW) and EM Field (EMF) on the extent to which representational aspects of these simulations influenced learning outcomes. EM Field runs on standard desktop computers and presents learners with 2-D representations of electric fields and electric potential, using quantitative values to indicate strength [Trowbridge & Sherwood, 1994]. To make the two learning environments comparable, we designed lessons to utilize only those features of MaxwellWorld for which EM Field had a counterpart; this limited version of MaxwellWorld we designated MW_L. Thus, the primary differences between the simulations were representational dimensionality (EMF's 2-D vs. MW_L's 3-D) and type (EMF's quantitative vs. MW_L's qualitative). See Figure 9.

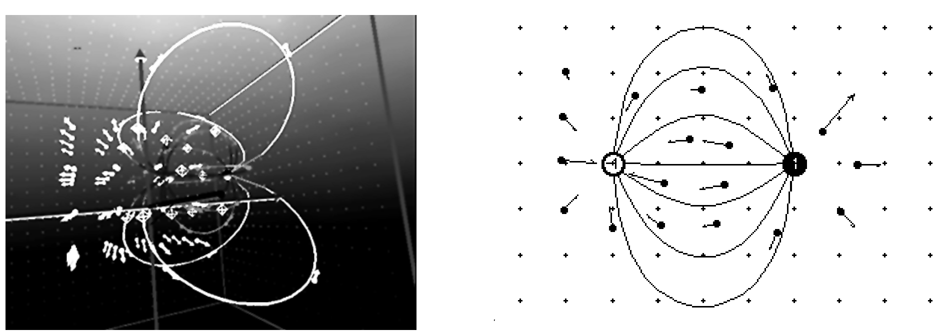

Figure 9. A dipole with field lines and test charge traces in MW and EMF.

In the second stage of the study, we utilized MaxwellWorld's full range of capabilities (including multisensory input) to ascertain the value these features added to the learning experience. Through the pre-test for phase two, we also examined the extent to which students, after a period of five months, retained mental models learned in either environment. Through this two-stage approach, we hoped to separate the relative contributions of 3-D representation vs. multisensory stimulation as instrumental to the learning potential of virtual reality.

During stage one, we examined whether representational aspects of the microworlds influenced learning outcomes. Fourteen high school students completed lessons in MW_L or EMF. Lessons leveraged the visual representations used in EMF and MW_L. During stage two, we examined the "value added" by unique VR features (e.g., multisensory cues) supported by MaxwellWorld. Seven EMF and MW_L students returned for stage two approximately 5 months after participating in stage one. All students received an additional lesson in the full version of MW that utilized multisensory cues as well as visual representations. During both stages, we examined pre- and post lesson understanding for each of the groups. We also assessed stage one retention for those students that returned for stage two. Finally, we examined whether factors such as motivation, simulator sickness, and usability differed across groups and whether these predicted learning outcomes.

Below is a summary of stage one outcomes:

- Both groups demonstrated significantly better conceptual 2-D and 3-D understanding post-lesson than pre-lesson. (All t-tests were significant at $p<.05$.) Therefore, lessons in both EMF and MW_L were meaningful.

Learning	**Post-Lesson**		**Retention**	
	EMF	MW	EMF	MW
Concepts	.58	.70	.69	.66
	F(1,11) = 3.17*		*F*(1,5) = .27	
2-D sketches	.80	.82	.42	.43
	F(1,11) = .24		*F*(1,5) = 0.00	
3-D demos	.67	.87	.31	.57
	F(1,11) = 9.99*		*F*(1,5) = 2.40	

Table 1. Adjusted post-lesson, retention means, and ANCOVA outcomes for stage 1 (covariate = pre-lesson scores). "*" indicates F is significant at $p<.05$.

- MW_L students were better able to define concepts than EMF students. Although not statistically significant, differences also occurred in the students' ability to describe electric fields in 3-D on the test given to measure retention after five months. See Table 1.

- MW_L students did not perform any worse than the EMF students at sketching concepts in 2-D. While MW_L students performed better on the force sketches, they performed worse on the sketches relating to potential**,** resulting in total sketch scores that were similar for the two groups. An explanation for this outcome may be that representations of force (lines and arrows) are more easily translated from 3-D to 2-D than representations of potential (surfaces). See Table 1.

- MW_L students were better able to demonstrate concepts in 3-D than EMF students. For example, despite the inherent three-dimensionality of the lessons and demonstration exercises, all but one EMF student restricted answers to a single plane, drew lines when describing equipotential surfaces, and used terms such as "oval" and "line." In contrast, MW_L students described phenomena using 3-D gestures and phrases such as "sphere" and "surface." Although not statistically significant, differences also occurred in the students' ability to describe electric fields in 3-D on the retention test. See Table 1.

- Student ratings indicated that they felt more motivated by MW_L than EMF; experienced greater simulator sickness symptoms in MW_L than EMF; and had more trouble using MW_L than EMF. However, none of these factors significantly predicted learning outcomes, indicating that the unique capabilities of the virtual reality interface accounted for the differences in educational outcomes.

Data for stage two yielded insights into the value of multisensory representations:

- Students demonstrated significantly better understanding of concepts, 2-D sketches, and 3-D demos post-lesson than pre-lesson. (All t-tests were significant at $p<.05$.) Students learned from visual and multisensory representations used in the lesson. Ratings concerning multisensory representations (haptic and sound), post-lesson understanding, and student comments all suggest that students who experienced difficulty with the concepts found that multisensory representations helped them understand visual representations.

- Mean motivation, simulator sickness, and usability ratings were similar to the ratings for MW_L in stage one.

Both stages lend support to the thesis that immersive 3-D multisensory representations can help students develop more accurate and causal mental models than 2-D representations. Learning outcomes for stage one show that MW_L learners—more than EMF learners—were able to understand the space as a whole, recognize symmetries in the field, and relate individual visual representations (test charge traces, field lines, and equipotential surfaces) to the electric field and electric potential. MW_L students appeared to visualize the phenomena in 3-D, while EMF students did not.

Subjective ratings for stage one yielded converging evidence that the representational capabilities virtual reality enables were responsible for differences in learning. First, motivation, though higher in MW_L than in EMF, was not a predictor of learning. Second, despite MW_L's usability and simulator sickness problems, students learned more using this virtual environment than they did using EMF. In stage two, the enhancement of visual representations with multisensory cues appeared to facilitate learning, especially for students who had trouble grasping the concepts. Dede, Salzman, Loftin, & Sprague [accepted for publication] provides additional detail concerning this study, as well as other early research results for MaxwellWorld.

PaulingWorld

PaulingWorld is still under development and has not yet undergone formative evaluation. Currently, learners can view, navigate through, superimpose, and manipulate five different molecular representations: wireframe, backbone, ball-and-stick, amino acid, and space-filling models. See Figures 10 and 11 for some examples of these models.

We are working on extending PW to address concepts underlying quantum-mechanical bonding—the kinds of concepts that have no real-life referents, are difficult to represent, and are hard for students to comprehend. These concepts include probability density and wave functions; molecular bonding/anti-bonding orbitals; multiple, interacting determinants of bond angles and bond length; the role of electronegativity in ionic vs. covalent bonding; and three-dimensional molecular geometries—culminating in Pauling's seminal insights on Valence Shell Electron Pair Repulsion (VSEPR). To design the immersive multisensory representations and underlying scientific models we will use for quantum-mechanical bonding phenomena, we are coordinating our design activities with a NSF-funded project, "Quantum Science Across the Disciplines," led by Peter Garik at Boston University (http://qsad.bu.edu/).

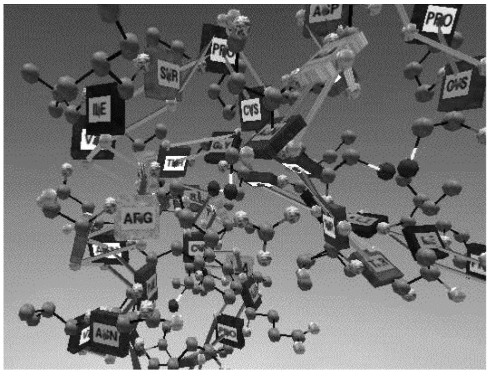

Figure 10. Ball-and-stick with some amino acids

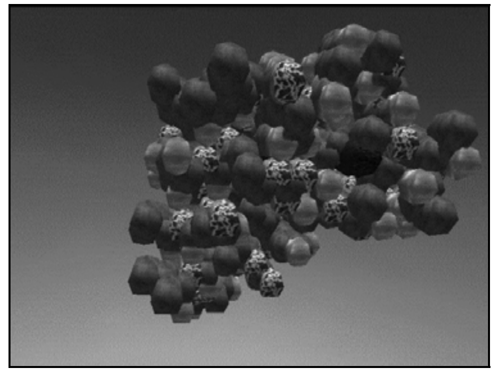

Figure 11. Spacefilling model

NewtonWorld

NewtonWorld addresses many well-documented misconceptions learners have about Newtonian mechanics. Clement [1982] refers to such misconceptions as “conceptual primitives”; these reflect erroneous generalizations from personal experience about the nature of mass, acceleration, momentum, Newton's laws, and the laws of conservation. Conceptual primitives form mental constructs, the understanding of which is a basic prerequisite for many higher-order concepts. Among common misconceptions about motion documented by Halloun & Hestenes [1985b] are the "motion implies force" notion, the “impetus” theory (an object’s past motion influences the forces presently acting on it), and "position-speed confusion" (i.e., ahead = faster).

Not only are these misconceptions strongly held by students entering physics courses, but they are very difficult to change with conventional approaches to instruction. Reinforced by their own real-world experiences, learners persist in believing that motion requires force (rather than that a change in motion requires force), that constant force produces constant velocity (rather than producing constant acceleration), and that objects have intrinsic impetus (rather than moving based on instantaneous forces). Thus, making these factors and their relationships salient is crucial to the teaching of Newton's laws and the laws of conservation.

Building on model-based pedagogical strategies for teaching complex scientific concepts, the challenges of learning Newtonian physics, and virtual reality's strengths and limits, we constructed learning objectives and general design guidelines for NewtonWorld. Learning goals are framed by the realization that students have deeply rooted misconceptions concerning Newton's laws, momentum, energy, and reference frames. Consequently, we determined that NewtonWorld should help learners to challenge and reconstruct these mental models. For example, after being guided through a series of inquiry activities focusing on conservation of momentum and energy, students should be able to identify important factors, accurately predict how each factor influences momentum and energy, describe the momentum and energy of objects under various dynamic and static conditions, explain how the laws are reflected in the behavior of objects, and use these insights to explain real world phenomena.

NewtonWorld's Original Design

In NewtonWorld, we rely on sensorial immersion to enhance the saliency of important factors and relationships, as well as to provide experiential referents against which learners can compare their intuitions. In our original version of NewtonWorld, learners can be "inside" a moving object and feel themselves moving; this three-dimensional, personalized frame of reference centers attention on velocity as a variable. Multisensory cues are used to further heighten the saliency of factors such as force, energy and velocity. Students begin their guided inquiry inside an immersive virtual environment in which gravity and frictional forces are set to zero, allowing observation of Newton's three laws operating without other superimposed phenomena clouding their perceived effects:

- Newton's first law states that, if the net force on an object is zero, an object originally at rest remains at rest, and an object in motion remains moving in a straight line with constant velocity.
- Newton's second law states that the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass. The direction of the acceleration is in the direction of the applied net force.
- Newton's third law states that, whenever one body exerts a force on a second body, the second body always exerts an equal and opposite force on the first body.

Studying the collision of objects also enables the introduction of other scientific principles, such as conservation of momentum and of energy and reversible conversions between kinetic and potential energy.

The original version of NewtonWorld provides an environment for investigating the kinematics and dynamics of one-dimensional motion. Once immersed in NewtonWorld, students spend time in and around an activity area, which is an open "corridor" created by colonnades on each side and a wall at each end (see Figure 12). Students interact with NewtonWorld using a "virtual hand" and a menu system. Learners can launch and catch balls of various masses and can "beam" (teleport) from the ball to 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 is represented by auditory and visual cues. The presence of potential energy before launch is represented by a tightly coiled spring, as well as via vibrations in the vest users wear. As the ball is launched (see Figure 13) and potential energy becomes kinetic energy, the spring uncoils and the energy vibrations cease. The balls then begin to cast shadows whose areas are directly proportional to the amount of kinetic energy associated with each ball. On (perfectly elastic) 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, the columns light and chime as the balls pass.

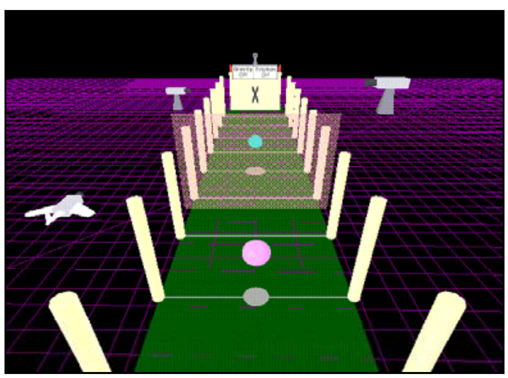

Figure 12. Above the corridor, showing cameras, balls with shadows, and the far wall

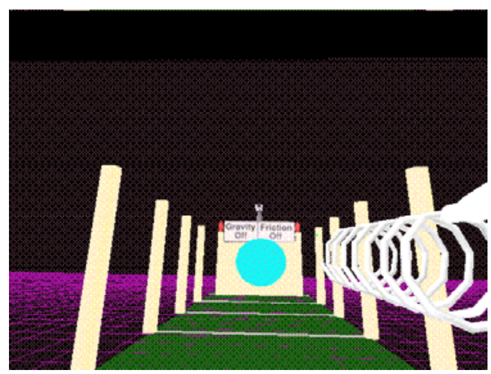

Figure 13. After launch, illustrating the spring-based launching mechanism

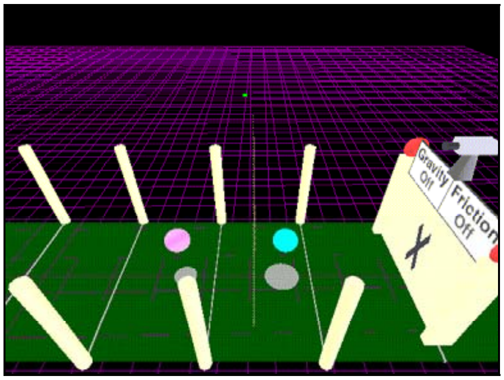

Figure 14. A collision seen from the center-of-mass reference frame

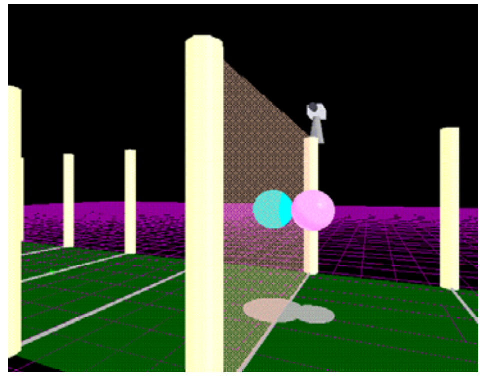

Figure 15. A collision seen from just outside a colonnade

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 (see Figure 14), a movable camera hovering above the corridor, etc. Figure 15 shows a collision seen from just outside one colonnade. These features aid learners in understanding the scientific models underlying Newton’s three laws, potential and kinetic energy, and conservation of momentum and energy.

In scaffolding the learning in NewtonWorld, our approach draws on recent research that emphasizes aiding learners to construct causal models as they experience dynamic, intriguing natural phenomena [Frederickson & White, 1992; White, 1993]. Phenomena are selected that exemplify misconceptions in learners' current models of reality, thereby heightening student interest by exhibiting counter-intuitive behaviors. Through game-like inquiry activities in simulations sequenced to present increasingly complex situations, students make predictions, conduct experiments, and derive qualitative rules against which they can assess and modify their predictions. For example, learners might be asked to predict the motion of an object as a force is applied to it; one rule a student might generalize (incorrectly) is "if a force is applied to an object, its velocity increases." 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.

To illustrate an activity a student might undertake in the original version of NewtonWorld, imagine that the learner is “inside” a ball that has an initial velocity relative to the corridor. Neither gravitational nor frictional forces are activated, and objects have a perfect coefficient of restitution (i.e., the balls will rebound with perfect elasticity and will not transfer kinetic energy to heat). The walls at the end of the corridor have infinite mass; the student (as a ball) has a unitary mass of 1. Via a sequence of experiences, the student is asked to answer the following questions: (1) If you launch a ball equal in mass to the ball that you are within, what will be the subsequent behavior of both balls? (2) What will occur if you "catch" the other ball when the two masses are moving in opposite directions--or in the same direction? (3) If instead you launch a ball whose mass is not equal to the mass of the ball you are within, will the balls' behaviors be different; if so, how? (4) What rules can you derive that predict the balls' dynamics in other similar situations?

By launching and catching balls of various masses, and viewing the collisions from various viewpoints (e.g., a ball, a camera at the center-of-mass, a camera outside the corridor, etc.), the student immersively experiences a variety of counter-intuitive phenomena. For example:

- the relative motion of the ball the student is within is affected by launching the other ball;
- the momenta of two unequal masses are equal but opposite after launch, but their kinetic energies are not;
- if the student catches a ball when it is moving with exactly opposite momentum to the ball he or she is within, both balls will come to a complete stop; and
- whether traveling in the same direction or in opposite directions at the time of collision, two balls of equal mass interchange relative velocities when colliding.

After observing one or more of the above phenomena, students are asked to describe what they observed, determine whether observations supported their predictions, and refine their predictions. After completing a series of related activities, students are encouraged to synthesize what they observed by describing and explaining relationships among important factors. Ultimately, our goal is for students to be able to transfer and generalize their insights concerning the phenomena they experienced in NewtonWorld to a wide variety of analogous real world situations.

NewtonWorld Evaluations

We have conducted several formative evaluations for our first version of NewtonWorld. As our design and evaluation is iterative, the original version of NewtonWorld evolved slightly from evaluation to evaluation. Therefore, we briefly describe how each evaluation impacted NewtonWorld's design.

Evaluating the learning experience with students. In the summer of 1994, we examined the earliest 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. Using each of four variations of the user interface (menu-based, gesture-based, voice-based, and multimodal) participants performed a series of "typical" and "critical" activities, thinking-aloud as they performed them. 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. Task strategies, task completion, error frequency, and student comments were recorded as they attempted each of the tasks. Following the sessions, students rated the ease of use of various aspects of the interaction, ranked interaction alternatives, and listed what they liked and disliked about the system. Below is a summary of the lessons we learned from this evaluation:

- Participants were comfortable with the bouncing ball metaphor, liked the virtual hand, and intuitively understood that this interface enabled them to interact with objects in the world. Seven of nine students ranked the multimodal interface above the others, and eight students used one or more of the options (voice, gestures, and menus) available to them while using the multimodal interface. Of the interaction alternatives, voice was the preferred and most error-free method of interaction. Menus also were well liked, yet students experienced difficulty selecting menu items. Gestures were unreliable and the least preferred interaction method. Additionally, all students experienced slight to moderate levels of discomfort and eyestrain after wearing the HMD for approximately 1-1/4 hours (even with one or two breaks during that period).

- Student comments suggested that the ability to observe phenomena from multiple viewpoints was motivating and crucial to understanding. However, additional visual, auditory, or tactile cues seemed necessary to smooth interaction and to help the students focus on important information.

- Students interpreted the size of the ball as a cue for mass. From a usability perspective, this might suggest utilizing size as an indicator of mass. However, from an educational perspective, this is problematic, as such a representation reinforces the misconception that larger objects are more massive. Using color to distinguish the balls, and labels or color intensity as a cue for mass, meets both usability and learning criteria.

Based on these outcomes, we made a number of modifications to the early design of NewtonWorld. We maintained the ball metaphor and the general nature of the activities, but expanded the possible viewpoints from two to five and implemented the more flexible "beaming" (teleporting) method for moving among frames of reference. We also implemented sound cues to supplement visual cues.

Evaluating Design Concepts with Physics Educators. To obtain feedback and guidance from experienced educators, at the 1994 Summer Meeting of the American Association of Physics Teachers 107 physics instructors and researchers used NewtonWorld and gave us their insights. Participants observed a 10 minute demonstration of NewtonWorld via a computer monitor, then received a personal experience 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. Below is a summary of evaluation outcomes:

- A majority of those surveyed found the basic activities easy to perform. However, as with the students in the usability tests, many participants experienced difficulty using the menus and focusing the optics of the head-mounted display.

- A large majority of physics education experts felt that NewtonWorld would be an effective tool for demonstrating Newtonian physics and dynamics. Participants were enthusiastic about the three-dimensional nature of this learning environment and appreciated the ability to observe phenomena from a variety of viewpoints. However, several participants expressed concerns regarding the limitations of the prototype and encouraged expanding the activities, environmental controls, and sensory cues provided.

- Several participants felt a broader field-of-view would have improved their experiences; however, some reported slight eye strain and dizziness. Thus, identifying an appropriate solution to this problem was difficult because increased field-of-view could have resulted in usability problems due to eye strain and nausea.

Physics educators’ feedback indicated that, while we had improved upon the version of NewtonWorld tested in the usability sessions, we needed to more fully utilize the multisensory nature of VR. We expanded the interface to include a haptic vest and more extensive visual and sound cues. We also refined the menus to make selecting menu items easier. Finally, because the menus were not used during the observation portion of activities, we changed the menu bar to a small 3-Ball icon, resulting in an increased visual field-of-view and improving users' abilities to experience motion and see important visual cues.

Evaluating Learning. From December 1994 through May 1995, we conducted formative learnability evaluations on NewtonWorld, focusing both on the importance of the multisensory experience and on reference-frame usage in learning.

Thirty high school students with at least one year of high school physics participated. Each individual 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 evaluate 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 helped to determine whether this “first generation” version of NewtonWorld aided students in better understanding relationships among force, motion, velocity, and energy. Below is a summary of the outcomes of these evaluations:

- 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.

- Single session usage of NewtonWorld was not enough to dramatically transform users' mental models. Students did not demonstrate significant learning from pre- to post-test knowledge assessments, and no significant differences were found among groups.

- Students appeared to be more engaged in activities when 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.
- Most learners 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 students experienced difficulty with eye strain, navigating, and selecting menu items. At times, these problems appeared to distract users from the learning activities and contributed to fatigue.

Outcomes encouraged us to further refine the interface and learning activities. We moved the menu from its fixed location in the HMD's field-of-view to the user’s second virtual hand, allowing users to freely adjust menu position and to judge menu location based on the physical position of their own hands. We also investigated ways to enhance multisensory cues. Perhaps the most significant design change, however, was our reconceptualization of NewtonWorld to shift the emphasis of educational activities. Our analysis of the learnability data suggested 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 Aristotelian mental models just at the time when young learners are developing these misconceptions might become a foundation for a less difficult, accelerated transition to a Newtonian paradigm.

The Redesign of NewtonWorld

We are currently in the process of making substantial changes to the original version of NewtonWorld. As mentioned in the previous section, we have reconceptualized the learning objectives and target audience for NewtonWorld. We will use the revised NewtonWorld to target younger users and to focus specifically on Newton's laws as they relate to the conservation of momentum.

Since NewtonWorld was the first virtual environment we built, its original interface did not incorporate sophisticated features we developed in designing MaxwellWorld and PaulingWorld. Accordingly, we are redesigning NewtonWorld to take advantage of these new capabilities. On the next page are two sketches illustrating our redesign, at present under construction. New features include a “scoreboard” (Figure 16) to aid learners in relating qualitative and quantitative representations, an improved interface based on a “endless roadway” metaphor (Figure 17), shifts in the representations used to connote mass and momentum, and the inclusion of both perfectly elastic and perfectly inelastic collisions.

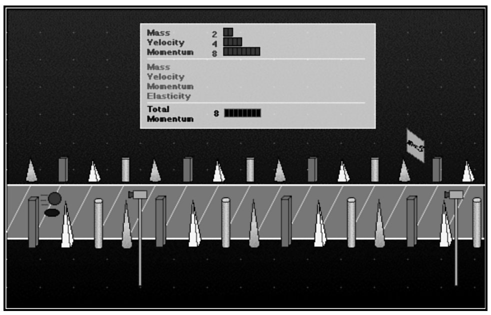

Figure 16. Redesigned NewtonWorld showing “scoreboard” and “roadway”

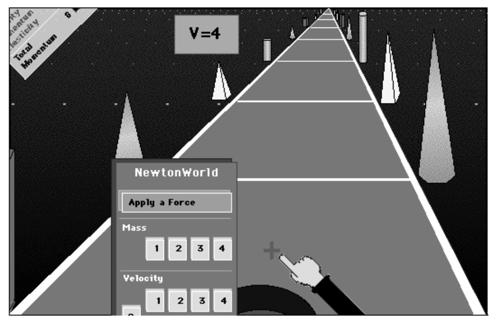

Figure 17. Within the “roadway” view

This “second generation” version of NewtonWorld is intended to target concepts relating to Newton's laws and the conservation of momentum, presented at a level appropriate for learners around grades five through seven. Our revision of NewtonWorld has three levels of activities. In Level 1, the student can explore the relation between force, mass, velocity and momentum with a single object. By allowing the learner to observe the behavior of one object as a function of mass, force and velocity, the student can better understand the contribution of mass and velocity to momentum before observing the motions of two colliding objects. In Level 2, two objects—each of varying masses, velocities, and elasticities—are involved in collisions. These collisions allow students to observe the relationships between mass, velocity, momentum, conservation of momentum, and elasticity. Level 3 will incorporate aspects of Levels 1 and 2 and will test students' mastery of concepts within a game-like environment.

A major enhancement to the revised version of NewtonWorld is a scoreboard that displays information about the mass, velocity, momentum, and elasticity of each object, as well as the total system momentum. This information is represented both numerically and as a graphical segmented line. The latter allows for rapid approximation by learners (e.g.., large velocity and large mass yields large momentum), whereas the numerical value will be helpful when students need more exact values of variables.

In a shift from the original version of NewtonWorld, mass is represented visually by different levels of transparency. The more massive an object, the greater its opacity; an object of low mass will be relatively transparent (but still readily visible). Elasticity is also represented visually, via textures. Elastic objects appear shiny and hard, while inelastic objects seem soft and "squishy" like a piece of gum. Momentum is represented by haptic cues (differing intensities of haptic vibration) and visual cues (the areas of the shadows under the objects). This is a change from the original version of NewtonWorld, in which shadows represented kinetic energy. As an added feature in the new version, the total momentum between two objects involved in the collision is represented by a cloud hovering above and between the two objects.

Evaluating Redesign Concepts with Teachers and their Students. We involved teachers and students in the formative stages of NewtonWorld's redesign. Specifically, we wanted (1) to gauge students' level of understanding of the concepts covered in NewtonWorld - Newton's laws and the conservation of momentum, (2) to validate learners' interest in the kinds of activities we planned to use in Levels 1 and 2 of NewtonWorld, and (3) to generate ideas about designing motivating and educational activities for NewtonWorld.

We began this process by interviewing three teachers from the 5th, 7th, and 8th grades concerning the skills of their students and the content and learning activities of NewtonWorld. (As described below, we later conducted focus groups with students in their science classes.) The teachers helped us understand which scientific terms might be familiar and how they had been covered in the curriculum. They also aided our thinking about how to work with different age levels in a focus group setting.

We then conducted three focus groups (one per teacher). Fifth grade students represented a wide range of academic performance. The seventh grade students were in a gifted-and-talented science class and embodied the top of their class with respect to academic achievement. Eighth grade students were from an average class and represented a wider range of abilities than the GT students. In each case, about 30 students participated in the focus group; in all cases, approximately equal proportions of males and females were involved. Through this strategy, we obtained insights from students of a broad range of academic capabilities.

Focus group activities included: (1) an interactive discussion of concepts relating to Newton's Laws and conservation of momentum; (2) completion of a series of learning activities using a 2-D simulation of NewtonWorld programmed in the Macintosh-based Interactive Physics II™ software; and (3) a brainstorming session in which students identified liked and disliked features of their favorite video and educational games and generated ideas for game-like activities in NewtonWorld. Below is a summary of focus group outcomes:

- *NewtonWorld concepts.* Topics discussed included mass, (variable and zero) gravity, velocity (for the 5th graders, we referred to velocity as "speed" to the left and right), elasticity (in the framework of gooey or bouncy), and momentum. All levels of students were unfamiliar with some of the scientific terminology necessary to describe Newton's laws and the law of conservation of momentum. Therefore, prior to completing learning activities, we defined key factors and found that they quickly grasped these definitions. Upon relating factors during the learning activities, we found that the 5th graders received the physics content well above expectation. Compared to older students, fifth graders progressed through the activities a little more slowly and had more difficulty predicting how factors interrelated, but demonstrated increased understanding as the sessions progressed, as well as a high degree of enthusiasm and intellectual curiosity. These young learners seemed quite capable of comprehending this material. Although most 7th grade and 8th grade students were able to define gravity and speed, some hesitation and disagreement arose in each group about mass and momentum. They also experienced difficulties predicting the outcomes of some collisions. Like the 5th grade students, older students demonstrated increased understanding as the sessions progressed.

- *NewtonWorld simulations based on the Interactive Physics II software.* As a group, students engaged in a series of activities similar to those planned for our immersive, multisensory NewtonWorld, but contextualized in a two-dimensional microworld with no multisensory capabilities. The format used to present activities to the group was the predict-observe-compare cycle central to our research. Students responded positively to this pedagogical approach, and the progression of activities (discussing single objects in Level 1 and discussing collisions in Level 2) also worked well for all groups of students. Students, the youngest group in particular, seemed to be motivated by the activities.

- *Game-like activities.* Brainstorming revealed that all groups of students were attracted to adventure games with good graphics (e.g., Dark Forces, Outlaws, Doom). Several racing games and fighting games were mentioned, but for the most part the focus was on adventure games. Students felt that the flexibility of the environment (e.g., having various types of activities and levels of difficulty) is an important part of making it game-like. The following features were seen as assets in educational games: side activities, puzzles, reward factors (for example, a “Hall of Fame”), and multiple representations of information (e.g., math presented not only as numbers, but also as pictorial symbols). In general, an impression left by all three focus groups was that students seemed appreciative of games in which players have ultimate control over their fate.

On balance, the focus groups' results have reinforced our strategy of targeting younger learners just when they are developing Aristotelian, rather than idiosyncratic, concepts of motion. Additionally, these discussions validated our content and approach. Finally, the focus groups helped us generate design ideas for the Level 3, in which we want to engage students in game-like activities where success depends on the application of concepts learned in levels 1 and 2. However, making Level 3 game-like for students creates some task goals that are somewhat removed from our primary objective of mastering scientific concepts. Therefore , careful design of Level 3 will be required to ensure that motivational features reinforce learning rather than interfering with it.

By the end of summer, 1997, we hope to begin formative evaluations of the revised version of NewtonWorld, eventually doing a comparative study to a comparable two-dimensional virtual environment (similar to the MaxwellWorld/EM Field contrast described earlier).

Lessons Learned

For all three of our virtual worlds, the research we have conducted to date provides insights into strategies for investigating advanced learning technologies, as well as assessments of virtual reality's potential for teaching abstract science. Lessons learned concerning formative research on advanced educational technologies are:

- A learner-centered development approach that focuses simultaneously on the learning experience , the learning process, and learning outcomes has been invaluable in yielding insights into the strengths and weaknesses of VR technology. Additionally, continuous evaluation of progress through lessons coupled with assessments of factors such as usability, simulator sickness, and motivation has helped us to explain learning outcomes. We would expect such an approach to work for the evaluation of any educational technology.
- We have found talk-aloud protocols employing a cycle of prediction-observation-comparison are highly effective for monitoring the learning process, as well as for identifying usability problems.
- A careful initial analysis of learner needs and capabilities/limits of the technology were critical to understanding how to leverage that educational medium to support the learner. However, fully anticipating learner needs is not possible. The iterative process of design and evaluation has helped us make our worlds more enjoyable and educational.

- Spreading lessons over multiple VR sessions may be more effective than covering many topics in a single session. We have found, while students began to challenge their misconceptions during the first session, many had trouble synthesizing ideas during post-testing. Fatigue and cognitive overhead in mastering the interface may have influenced these outcomes. When we spread lessons over multiple, shorter sessions, students were better able to retain and integrate information in post-testing.

Additionally, we have discovered several challenges that must be considered when designing immersive educational VR worlds.

- To help learners utilize educational virtual worlds, calibrating the display and virtual controls for each individual is vital. Additionally, monitoring and systematically measuring "simulator sickness" is important, as its onset signals interface problems and can explain why a learner is having trouble with certain activities.
- Students exhibit noticeable individual differences in their interaction styles, abilities to interact with the 3-D environment, and susceptibility to simulator sickness.
- Immersion presents some challenges for lesson administration. For example, students in the head-mounted display cannot access written instructions or complete written questions. Verbal interaction works well.
- Today's head-mounted displays are a major source of discomfort for users, presenting a threat to usability and learning.
- Standard approaches to building 2-D microworlds (GUIs, and activities based on a planar context) do not scale well to 3-D worlds. Multimodal interaction and multisensory communication are important parts of an immersive experience. The development of VR interface tools that facilitate these interactions is a much-needed advance.
- Our work with students and teachers in ScienceSpace suggests that collaborative learning can be achieved by having several learners take turns administering lessons, recording observations, and exploring the virtual worlds.

Finally, we have found the following aspects of immersive VR technology promising for learning complex science.

- Multimodal interaction (voice, virtual, and physical controls) facilitates usability and appears to enhance learning. Multimodal commands offer flexibility, allowing individuals to adapt the interaction to their own style and to distribute attention when performing learning activities. For example, some learners prefer voice commands so they need not shift attention from phenomena of interest to manipulating the menu system.

- Multisensory cues can engage learners, direct their attention to important behaviors and relationships, help them understand new sensory perspectives, prevent errors through feedback cues, and enhance ease of use.
- Enabling students to experience phenomena from multiple perspectives appears to facilitate the learning process. As discussed later, we plan additional research to more fully investigate the potential leverage frames-of-reference can provide.
- Three-dimensional representations seem to aid learners in understanding phenomena that pervade physical space. Being immersed in a 3-D environment is also motivating for learners.
- Qualitative representations (e.g., shadows showing kinetic energy in NewtonWorld) can make salient crucial features of phenomena and representations, thereby aiding learning
- The creation of new representations that leverage VR's features (e.g., enabling students to become objects or feel force and energy) may help students challenge misconceptions formed through traditional instruction, as well as aid learners in developing correct mental models.

Next Steps in Our Virtual Reality Research

Over the next two years, we plan to extend our current research on the ScienceSpace worlds along several dimensions. Described below is a study we will conduct on MaxwellWorld to examine the contribution of immersive frames-of-reference to understanding complex science concepts. Using the revised version of NewtonWorld, we also intend to examine how, by facilitating innovative types of student collaborations, virtual reality may enhance the nature of social constructivist learning. These two planned studies are described in more detail below. In addition, as PaulingWorld matures, we will study whether multisensory immersion enables students to master counterintuitive chemistry concepts such as complex as quantum-level phenomena. Finally, to examine challenges in curriculum integration and in classroom implementation, we will move our VR worlds out of laboratory environments into pre-college classroom settings.

Understanding the Potential Utility of Frames-of-Reference for Learning Complex Science

We believe that making the learning experiences more perceptual, we can augment their power for visualizing complex information and for learning. We have documented that adding multisensory perceptual information aided students struggling to understand the complex scientific models underlying NewtonWorld and MaxwellWorld. Providing experiences that leverage human pattern recognition capabilities in three-dimensional space, such as shifting among various frames-of-reference (points of view), may also make the learning experience more perceptual. These enhanced "perceptualization" techniques create experiences that may increase the saliency and memorability of abstract scientific concepts and potentially benefit learning.

Psychological research on spatial learning, navigation, and visualization suggests that frames-of-reference (FORs) make salient different aspects of an environment and influence what people learn [Barfield, Rosenberg, & Furness, 1995; Ellis, Tharp, Grunwald, & Smith, 1991; Darkin & Sibert, 1995; Presson, DeLange & Hazelrigg, 1989; Thorndike & Hayes-Roth, 1982]. Although there are numerous FORs, most classification systems converge to two types: exocentric or egocentric [McCormick, 1995; Wickens & Baker, 1995]. See Figure 18 for an example of FORs in MaxwellWorld.

By using frames-of-reference (FORs) in virtual reality, we can provide learners with experiences that they would otherwise have to imagine. For example, we can enable students to become part of a phenomenon and experience it directly. Alternatively, we can let learners step back from the phenomenon to allow a global view of what is happening. One frame-of-reference may make salient information that learners might not notice in another frame-of-reference. Further, multiple frames-of-reference might help students to fill in gaps in their knowledge and to become more flexible in their thinking.

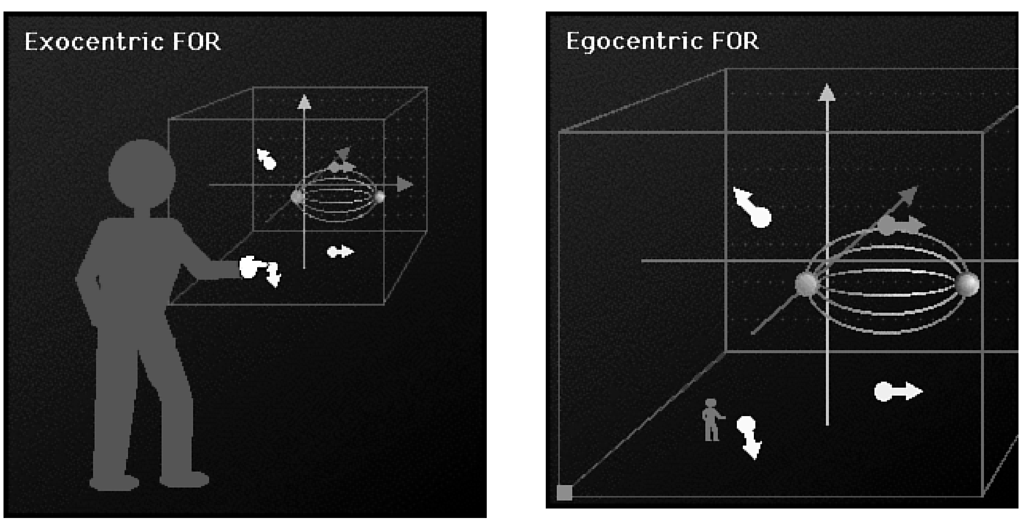

Figure 18. Exocentric versus Egocentric Frames of Reference in MaxwellWorld

In the MaxwellWorld study on FORs and perceptualization that Salzman will conduct as her doctoral dissertation, the two concepts learners will be asked to master are 1) the distribution of force in electric fields and 2) the motion of test charges through electric fields. These two learning tasks were selected because they differ in the extent to which global and local knowledge is important—the kinds of knowledge believed to be afforded by different FORs. Comprehending distribution depends more heavily on global judgments than local judgments, while understanding motion requires more local judgments than global judgments.

Salzman will assess students' mastery of scientific concepts at two levels: descriptive and causal. Descriptive mastery indicates that an individual remembers the representation and its behavioral interrelationships with other representations in the model; causal mastery shows that he/she understands what the representations and their pattern of relationships mean about the nature of the reality. The latter reflects a deeper understanding of the information and is what we seek to accomplish in teaching learners about scientific phenomena. Salzman will examine both descriptive and causal performance on FOR learning tasks as a means of providing insights into the strengths and weaknesses of FORs and perceptualization in mastering various kinds of complex information.

This study may bring us one step closer to understanding how we can leverage the human perceptual system in the visualization process. Given that the ability to comprehend complex scientific concepts is becoming increasingly important for success for both workers and citizens, investigating how to enhance people's perceptual abilities with augmented visualization tools is an important issue. In addition, we intend to extend our explorations on how multisensory immersion influences learning. For example, various sensory modalities can provide similar, mutually confirming input or can increase the amount of information conveyed to the learner through each sensory channel conveying different data. Little is known about what level of redundancy in sensory input is optimal for learning and about how much information learners can process without sensory overload. Moreover, each sense uniquely shapes the data it presents (e.g., perceived volume and directionality of sound is nonlinear, varies with the pitch of the input, and is idiosyncratic to each person). This poses complex considerations in deciding which sensory channel to use in presenting information to learners.

The nature of the electric field domain should be sufficiently representative of other kinds of visualization problems that we can gain insights not only into how to leverage FORs for learning, but also to utilize perceptualization to facilitate scientific discovery and the communication of complex ideas in research and industry. However, additional studies will be necessary to help understand how FORs, multisensory cues, and other features can be integrated in visualization tools. Virtual reality provides a good research environment for exploring these design issues, as well as for exploring how multisensory immersion shapes collaborative learning.

Immersive Collaborative Learning as a Means of Enhancing the Shared Construction of Knowledge

As a near-term research initiative in our ScienceSpace worlds, we will investigate the effectiveness of collaborative learning situations in which three students in the same location rotate roles among (1) interacting with the world via the headmounted display, (2) serving as external guide, and (3) participating as a reflective observer. We also plan to experiment with collaborative learning among distributed learners inhabiting a shared virtual context. The student would act and collaborate not as himself or herself, but behind the mask of an "avatar": a surrogate persona in the virtual world. Loftin [1997] has already demonstrated the capability of two users simultaneously manipulating a shared immersive environment using communications bandwidth as low as a standard ISDN telephone line. By adapting military-developed distributed simulation technology, we could scale up to many users in a shared, interactive virtual world.

Collaboration among learners' avatars in shared synthetic environments may support a wide range of pedagogical strategies (e.g., peer teaching, Vygotskian tutoring, apprenticeship). In addition, adding a social dimension aids in making technology-based educational applications more intriguing to those students most motivated to learn when intellectual content is contextualized in a social setting. However, in virtual environments, interpersonal dynamics provide leverage for learning activities in a manner rather different than typical face-to-face collaborative encounters. Various researchers [Turkle, 1995; Bruckman & Resnick, 1995; Sproull & Kiesler, 1991], as well as virtual community participants like Rheingold [1993], are documenting the psychological phenomena that result when people interact as avatars or depersonalized entities rather than face-to-face. These include disinhibition, fluidity of identity, mimesis, and a wider range of group participation via increased interaction from people who are shy or who want time to think before responding.

Virtual environments that illustrate the challenges and opportunities of these psychological phenomena for education include learning-oriented MUSEs and MOOs. These are text-based "worlds" in which users can assume fluid, anonymous identities and vicariously experience intriguing situations cast in a dramatic format. In contrast to standard adventure games, where one wanders through someone else's fantasy, the ability to personalize an environment and to receive recognition from others for a contribution to the shared context is attractive to users (as is also true in face-to-face constructivist learning). The continual evolution of shared virtual environments based on participants' collaborative interactions keeps these educational settings from becoming boring and stale.

We believe that our ScienceSpace worlds offer an intriguing context for extending such work on “social constructivism” in virtual environments. Physical immersion and multisensory stimulation may intensify many of the psychological phenomena above, and “psychosocial saliency” may be an interesting counterpart to perceptual saliency in enhancing learning. Important questions to be answered include the relative value of providing learners with graphically-generated bodies and the degree to which the “fidelity” of this 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). Our research plans include studies to explore these possibilities.

Conclusion

At the beginning of this chapter, we argue that our research is important in part because information technology is developing powerful capabilities for creating virtual environments. Within the next decade, via the videogame industry, devices capable of multisensory immersion will be ubiquitous in rich and poor homes, urban and rural areas. To compete with the captivating, but mindless types of entertainment that will draw on this power, educators will need beautiful, fantastic, intriguing environments for learning. Project ScienceSpace is beginning to chart these frontiers, as well as revealing which parts of VR’s promise are genuine, which parts are hype.

Exploring the potential of home-based devices for learning is particularly important because of the high costs of keeping school-based instructional media current with technologies routine in business settings. The goal espoused by many today of multimedia-capable, Internet-connected classroom computers for every two to three pupils carries a staggering price tag—especially if those devices are obsolete five to seven years after installation. While providing adequate, sophisticated school-based instructional technologies is extremely important, it is vital to leverage this investment via simultaneous utilization of entertainment and information-services devices in family and community settings. In other words, using technology to aid educational reform through systemic innovation must occur on two levels simultaneously: drawing one boundary of the system around the school, with student-teacher-technology partnerships; and another system boundary around the society, with classroom-family-workplace-community-technology partnerships. Such an innovation strategy necessitates developing learning materials—including “edutainment”—for emerging technologies such as Web-TV and virtual reality [Dede, 1996].

In the long run, research on multisensory immersion will also produce another important outcome: a deeper understanding of the nature of human learning. As biological organisms, our brains have evolved very sophisticated mechanisms for comprehending three-dimensional spatial environments that provide input on various sensory modalities. To date, however, these "perceptualized" learning capabilities have provided little aid in mastering phenomena whose causes are abstract, complex, or counterintuitive. Being a worker and citizen in the 21st century will require comprehension of sophisticated scientific content, material most people do not learn through the best of the instructional approaches available today. Via the types of representations and learning activities Project ScienceSpace is exploring, insights are emerging into how we can leverage the full capabilities of the brain—and advanced information technologies—to attain this type of learning.

For more information

Further information, including Quicktime™ and Quicktime VR™ files for "viewing" the worlds we have developed, can be obtained from our website: http://www.virtual.gmu.edu.

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