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The Development of a Virtual World for Learning Newtonian Mechanics

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Abstract. We are collaboratively designing "ScienceSpace," a collection of virtual worlds designed to explore the potential utility of physical immersion and multisensory perception to enhance science education. This paper describes the creation and formative evaluation of NewtonWorld, a virtual environment for investigating the kinematics and dynamics of one-dimensional motion. Through this research, we are developing design heuristics, assessment methodologies, and insights about multisensory learning generalizable to a wide range of educational environments. We are also gaining an understanding the strengths and weaknesses of virtual reality as a vehicle for learning.

1 Introduction

1.1 Virtual Reality's Potential Value in Science Education

Exemplary pedagogy in science education is based on two principles. First, instruction should develop learners' abilities to intuitively understand how the natural world functions before inculcating the formal representations and reasoning skills that scientists use. In other words, fostering in students the capability to qualitatively predict the behavior of the universe is initially more important than teaching them to manipulate quantitative formulas. Second, instruction should help learners evolve their existing mental models to more accurate conceptions of reality. Students are not empty vessels to be filled with theories; they have firmly held, often erroneous beliefs about how reality operates, from which they must be weaned by guided inquiry experiences that reveal the shortcomings of their current conceptual frameworks.

To date, uses of information technology to apply these two pedagogical principles have centered on creating computational tools and 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.

However, high-performance computing and communications capabilities create a new possibility. Like Alice walking through the looking glass, learners can immerse themselves in distributed, synthetic environments, becoming "avatars" (computer-graphics representations that serve as personas of human participants in the virtual world) who collaborate and learn-by-doing, using virtual artifacts to construct knowledge [Walker, 1990]. The key features that virtual reality adds to current educational media are:

— immersion: the subjective impression that a learner is participating in a "world" comprehensive and realistic enough to induce the willing suspension of disbelief. Also, inside a head-mounted display the learner's focus of attention is captured in the virtual world, without the distractions presented in many other types of educational environments.

— telepresence: simultaneous presence in a virtual environment by geographically separated learners.

— high-bandwidth communication [Regian, Shebilske, & Monk, 1993]. 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. Such multisensory stimulation may prove valuable in prompting learning and recall.

— motivation [Pimentel & Teixeira, 1993]. Learners are intrigued by interactions with well designed immersive environments, inducing them to spend more time and concentration on a task.

— multiple representations and three-dimensional frames of reference. Spatial metaphors can enhance the meaningfulness of data and provide qualitative insights [Erickson, 1993]

Evolving beyond technology-mediated interactions between students and phenomena to technological instantiation of learners themselves and reality itself shifts the focus of constructivist education: from peripherally enhancing how a student interprets a typical interaction with the external world to "magically" shaping the fundamental nature of how learners experience their physical and social context.

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 artificial 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 world. The impression is that of being inside an artificial reality 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. Because common sense responses to physical stimuli work in artificial realities, the learner quickly develops feelings of mastery, rather than the helplessness and frustration that are typical when first attempting to use an unfamiliar computer interface or operating system.

The virtual reality interface has the potential to complement existing approaches to science instruction through creating immersive inquiry environments for learners' knowledge construction. By themselves becoming part of a phenomenon (e.g., a student becomes a point-mass undergoing collisions in a frictionless artificial reality), learners gain direct experiential intuitions about how the natural world operates. In particular, good instructional design can make those aspects of virtual environments useful in understanding scientific principles most salient to learners' senses. As one illustration, in two-dimensional Newtonian microworlds students often ignore objects' velocities, instead focusing on position. In a virtual reality environment, learners themselves are moving, centering attention on velocity as a variable; and designers can heighten this saliency by using multisensory cues to convey multiple, simultaneous representations of relative speeds. The novel perspective of oneself experiencing and shaping a natural phenomenon, instead of acting as a passive observer, is intrinsically motivating; and the fascination is heightened when another person's avatar is collaborating in the activity. Transducing data and abstract concepts (e.g., acceleration) into multisensory representations is also a powerful means of enhancing understanding [Dede, 1993]. Under these conditions, learners may be willing to displace previous misconceptions with alternative, more accurate mental models.

1.2 Challenges in Using Virtual Reality for Learning

However, many barriers intrinsic to current virtual reality technology can block students' constructivist mastery of scientific concepts. These challenges to educational design 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 3-D auditory cues may not be feasible or reliable, due to the unique configurations of each person's ears and the background noise characteristic of educational environments. Also, users have difficulty localizing 3-D sounds [Wenzel, 1992].

— Haptic feedback is extremely limited and expensive. Currently, 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]. For example, 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., perceiving motion, but feeling stationary).

— 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 these 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 problem 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 artificial reality they have created is set to zero. The cognitive dissonance this mismatch creates, due to conflicting sensory signals, can create both physiological problems (e.g., simulator sickness) and possibly false intellectual generalizations. This project will explore the extent to which manipulating learners' visual, auditory, and tactile receptors may induce subtle types of misconceptions about physical phenomena. The medium (virtual reality) must not detract from the message (learning scientific principles).

1.3 The Virtual Worlds of ScienceSpace

Since February, 1994, our project team has worked collaboratively to build "ScienceSpace," a collection of virtual worlds designed to explore the potential utility of physical immersion and multisensory perception to enhance science education. One objective of this project is researching whether sensorily immersive constructivist learning can remediate typical misconceptions in the mental models of reality held by many students. Another is studying whether mastery of traditionally difficult subjects (e.g., relativity, quantum mechanics, molecular-orbital chemical bonding) is enhanced by immersive, collaborative learning-by-doing.

Most people's mental models include misconceptions that stem from misinterpreting common personal experiences with complex real-world phenomena, in which many forces are simultaneously acting. For example, the deceptively universal presence of friction makes objects in motion seem to slow and stop "on their own," undercutting belief in Newton's First Law. As a result, most learners—including many science majors—have difficulty understanding physics 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. We are studying whether immersive, shared artificial realities that allow users to alter the laws of nature can empower learners' constructivist evolution of mental models to correct pervasive misconceptions. Some of this work extends into sensory immersion many ideas underlying 2-D constructivist microworlds for physics designed by researchers such as White [1993] and diSessa [Sherin, diSessa, & Hammer; 1993].

Of course, remediating misconceptions is not the only role that artificial realities designed for constructivist learning can play in science and technology education. Subjects such as quantum mechanics, relativity, and molecular bonding are difficult to teach in part because learners cannot draw analogies to personal experiences that provide metaphors for these phenomena. As a second objective in our research, we plan to construct immersive worlds that enable learners to experience near light-speed travel or quantum events, thus attempting to inculcate a instinctive, qualitative appreciation for these situations. This provides a phenomenological foundation for scientific principles that have been very challenging for learners to master.

ScienceSpace now consists of three worlds—NewtonWorld, MaxwellWorld, and PaulingWorld—in various states of maturity. NewtonWorld provides an environment for investigating the kinematics and dynamics of one-dimensional motion. MaxwellWorld supports the exploration of electrostatics, leading up to the concept of Gauss' Law. PaulingWorld, the most recent addition, enables the study of molecular structures via a variety of representations. This study focuses on our design and early formative evaluation of NewtonWorld.

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

2 The Design of NewtonWorld

We chose to begin our design of ScienceSpace with a virtual world that exemplify Newtonian mechanics and dynamics. This addresses many of the well-documented misconceptions that students typically carry with them as they enter—and leave—physics courses [Halloun, 1985a]. Clement [1982] refers to such misconceptions as “conceptual primitives”; these reflect erroneous generalizations from personal experience about the nature of mass, acceleration, momentum, charge, energy, potential difference, and torque (key concepts), as well as Newton's laws, conservation laws, the atomic model, and electron flow models for circuits (fundamental principles and models).

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 and Hestenes [1985b] are the "position-speed confusion" (i.e., ahead = faster), the "motion implies force" notion, and the “impetus” theory (an object’s past motion influences the forces presently acting on it). 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). Moreover, in group teaching such difficulties can easily go undetected, since students' superficial knowledge of formulas and symbolic manipulation techniques can mask their misunderstandings of underlying qualitative concepts.

In addition to providing a means for testing whether sensorily immersive environments can aid in remediating these misconceptions, artificial realities based on Newtonian mechanics and dynamics also present students with simple phenomena commonplace in their everyday experience (e.g., two objects colliding). This allows us to refine the interface to these virtual worlds and to conduct usability trials without confounding the results with learners' confusion due to unfamiliar content in the virtual environment. In our first NewtonWorld, students can alter the magnitudes of objects' masses, internal frictional forces, and coefficients of restitution. Visualization, sonification, and haptification features help learners sense attributes of objects in motion; further, learners can position themselves at various positions in the world and even attach themselves to objects, thereby enabling the comparison of different frames of reference. Through distributed simulation approaches, we can support shared interaction among geographically dispersed learners—even across merely moderate-bandwidth networks, such as the Internet—thus enabling telepresence and collaboration among learners' avatars in a virtual environment.

In NewtonWorld, students begin their guided inquiry in an artificial reality 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 in motion 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.

In teaching this material, our pedagogical approach draws on recent research that emphasizes aiding learners to construct causal models as they experience dynamic, intriguing natural phenomena [Frederickson & White, 1992]. 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 reflecting on how they construct a series of increasingly accurate rules, learners can develop an understanding of the epistemology of science and the research designs scientists utilize.

Research suggests that the use of multiple representations [McDermott, 1991] and of intermediate causal models [White, 1993] is crucial to learners mastering abstract scientific concepts, as well as formal techniques such as vector addition. Intermediate causal models parse the behavior of a system into a sequence of discrete causal events; as one illustration, in White's ThinkerTools microworld a moving object leaves behind a "wake" (a trail of small dots whose relative positions provide a history of the object's motion and velocity). Such representations are powerful for learning in part because they portray key domain constructs at the same qualitative level of abstraction as the intuitions and misconceptions students derive from everyday experiences. Also, the generic nature of these intermediate models facilitates learners' development of mental constructs that can be mapped onto multiple real-life contexts. In general, formal representations (such as vectors) should be introduced not as decontextualized abstractions, but as semi-tangible constructs that serve as means for prediction and explanation.

Our research builds on such a constructivist pedagogical framework, focusing on how virtual reality technology aids the evolution of concepts and causal models. (We do not expect physical immersion to provide additional leverage beyond two-dimensional microworlds for students to understand the epistemology of science.) Our design goals in creating NewtonWorld are:

— to provide multiple representations of natural phenomena;
— to support learning-by-doing through prediction, experimentation, and rule derivation;
— to enhance via multisensory input the saliency of variables influencing virtual world dynamics;
— to represent scientific concepts at intermediate levels of abstraction; and
— to create learning experiences that progress from simple to more complex situations.

In addition, our design of both the virtual context and learners' activities is based on studies of how computer simulations can leverage students' interest through shared fantasy, curiosity, and challenge [Malone & Lepper, 1985]. Due to their immersive nature, virtual reality environments can convey an eerie beauty that motivates creative exploration magically free from real-world constraints on one's ability to sense and act.

2.1 Learning, Design, and Evaluation Goals for NewtonWorld

With an understanding of the nature of students, the challenges of teaching Newtonian physics, and virtual reality's strengths and weaknesses, we constructed learning objectives and general design guidelines for NewtonWorld. Learning goals are framed by the realization that high school students have deeply rooted misconceptions concerning Newton's laws, momentum, energy, and reference frames. Consequently, we determined that NewtonWorld should help students 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.

Based on learning and technology issues, we determined that NewtonWorld should instantiate the following design goals: (1) support learn-by-doing through prediction, experimentation, and rule derivation; (2) represent physics at meaningful levels of abstraction; (3) make salient the factors influencing the behavior of objects and direct attention toward those factors; (4) provide multiple representations of the same phenomena; (5) allow multimodal interaction; (6) enable students to progress from simple to more complex learning activities; (7) motivate learners; and (8) facilitate smooth interaction.

Finally, we identified four important dimensions as critical to our evaluation framework:

- Usability: to assess the user interface by measuring performance on usability tasks, error rates and subjective ratings for ease of use.
- Learning: to determine whether students can progress through learning tasks in the environment and apply their learning to other domain specific problems.
- Usability vs. learning: to understand the relationship between usability and learning and to identify when the two goals may conflict. (Optimizing for usability may impede learning if it requires changes to the interface that rely on interactions or representations that are inappropriate for the learning task.)
- Educational utility: to demonstrate that the system is a better (or worse) teaching tool than other pedagogical strategies, comparing the quality and efficiency of learning among the alternatives.

Usability, learning, and their interactions can be assessed early through formative user evaluations. These rely on students to evaluate the virtual microworlds by having them use the system and provide feedback about their experiences. More elaborate research designs can establish the comparative educational utility of the virtual laboratory contrasted with alternative pedagogical methods. The evaluations we have done to date are formative in nature; consequently, our discussion focuses on usability and learning.

2.2 The Current Design of NewtonWorld

We used the goals outlined in the previous section to shape the design of NewtonWorld. We attempt to support learners through a 3-D microworld that not only contains the necessary information and activities for learning, but also leverages virtual reality's strengths and minimizes the impact of its limitations. Below we describe the version of NewtonWorld tested in the recent learning trials. This design reflects changes made as a result of the usability tests and surveys.

The physical interface to NewtonWorld is typical of current high-end virtual reality. The hardware we are using is a Silicon Graphics Onyx RE/2 reality engine, coupled with a Virtual Reality, Inc. VR4 head-mounted binocular display (HMD); a Polhemus FASTRAK magnetic orientation and position sensing system with a 3-Ball sensing unit (similar to a 3-D mouse); stereo sound; and a custom vest that delivers haptic sensations. This physical interface enables us to immerse the student in 3-D microworlds using the visual, auditory and tactile senses.

The software interface relies on 3-D generic representations of objects in motion. In NewtonWorld, students spend time in and around an activity area, which is an open "corridor" created by a colonnade on each side and a wall at each end. See Figure 1. Students interact with NewtonWorld using a "virtual hand" and a menu system, which they access by selecting the small 3-ball icon in the upper left corner of the HMD. Students can launch and catch balls of various masses and "beam" from the ball 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.

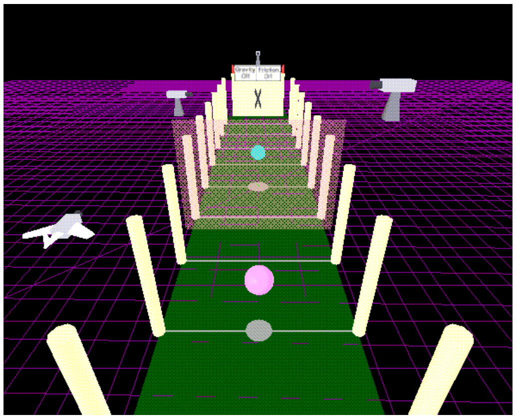

Figure 1: NewtonWorld from above an end wall.

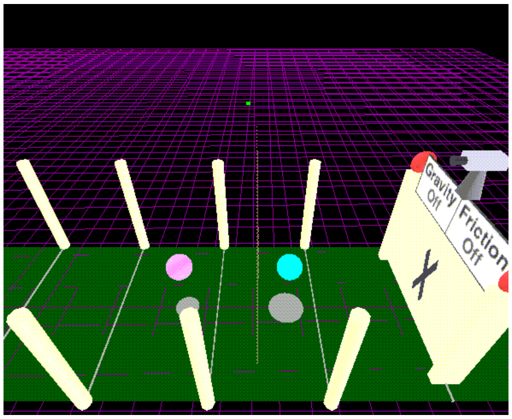

Figure 2: NewtonWorld from the center of mass.

Multisensory cues help students experience phenomena and direct their attention to important factors such as mass, velocity, and energy. For example, potential energy is made salient through tactile and visual cues, and velocity through auditory and visual cues. Currently, the presence of potential energy before launch is represented by a tightly coiled spring as well as vibrations in the vest. As the ball is launched and potential energy becomes kinetic energy, the spring uncoils and the energy vibrations cease. The balls now begin to cast shadows whose areas are directly proportional to the amount of kinetic energy associated with each ball. On impact, when kinetic energy is instantly changed to potential energy and then back to kinetic energy again, the shadows disappear, and the vest briefly vibrates. To aid students in judging the velocities of the balls relative to one another, we have the columns light and chime as the balls pass. Additionally, we provide multiple representations of phenomena by allowing students to assume the sensory perspectives of various objects in the world. For example, students can become one of the balls in the corridor, a camera attached to the center-of-mass of the bouncing balls, a movable camera hovering above the corridor, etc. Figure 2 shows what students might see from the center of mass camera.

To guide the learning process, we provide scaffolding that enables learners to advance from basic to more advanced activities. Students begin their guided inquiry in a world without gravity or friction, allowing them to perceive physics phenomena that are otherwise obscured by these forces. They can launch and catch balls of various masses and can view the collisions from several viewpoints. These activities provide an immersive experience of counter-intuitive phenomena. By instructing students to make predictions about upcoming events, directly experience them, and then explain what they experienced, we encourage learners to question their intuitions and refine their mental models. Once they understand relationships under idealized conditions (pure Newtonian dynamics), students will be able to "turn on" friction or gravity in future versions of NewtonWorld.

To illustrate an activity a student might undertake in the current version of NewtonWorld, imagine that the student 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. The student is initially 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.

3 Early Formative Evaluations of NewtonWorld

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

3.1 Initial Usability Evaluation

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

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

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

3.2 Physics Educators' Evaluation of Design Ideas

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

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

3.3 Early Evaluation of Learnability

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

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

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

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

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

4 Initial “Lessons Learned” From Our ScienceSpace Work

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

4.1 Design Heuristics

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

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

4.2 Assessment Techniques and Protocols

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

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

4.3 Challenges in Using Current Virtual Reality Interfaces

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

- Students exhibit noticeable individual differences in their interaction styles, abilities to interact with the 3-D environment, and susceptibility to simulator sickness.
- Immersion does present some challenges for lesson administration (for example, students in the head-mounted display are not able to access written instructions or to complete written questions.) We have found that verbal interaction works well.
- Limitations of the physical design and optics in today's head-mounted displays may cause discomfort for users. Since the visual display is an integral part of interaction and communication of information in these learning environments, these limitations are a current hindrance to usability and learning.
- Spreading lessons over multiple VR sessions appears to be more effective than covering many topics in a single session. While students began to challenge their misconceptions during a single 3-hour NewtonWorld session, many had trouble synthesizing their learning during post-testing. We believe that factors such as fatigue and cognitive overhead in mastering the interface influenced these outcomes. In contrast, our MaxwellWorld evaluations were completed over multiple sessions, tackling fewer topics during each session, and dedicating less time per session to pre- or post-testing. Reviews and post-tests demonstrated that students were better able to retain and integrate information over multiple lessons.

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

4.4 Insights About Learning and Knowledge Representation

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

- Multisensory cues can engage learners, direct their attention to important behaviors and relationships, help students better understand different sensory perspectives, prevent interaction errors through feedback cues, and enhance perceived ease of use.
- The introduction of new representations and perspectives can help students gain insights for remediating misconceptions formed through traditional instruction (e.g., many representations used by physicists are misleading for learners), as well as aiding learners in developing correct mental models. Our research indicates that qualitative representations (e.g., shadows showing kinetic energy in NewtonWorld, colors showing the magnitude of a force or energy in MaxwellWorld) increase saliency for crucial features of both phenomena and traditional representations.
- Allowing multimodal interaction (voice commands, gestures, menus, virtual controls, and physical controls) facilitates usability and seems to enhance learning. Multimodal commands offer flexibility to individuals, allowing them to adapt the interaction to their own interaction preferences and to distribute attention when performing learning activities. For example, some learners prefer to use voice commands so that they need not redirect their attention from the phenomena of interest to a menu system. (However, if virtual worlds are designed for collaborative learning, voice may be a less desirable alternative.)
- Initial experiences in working with students and teachers in MaxwellWorld suggest collaborative learning may be achievable by having two or more students working together and taking turns "guiding the interaction," "recording observations," and "experiencing activities" in the virtual reality. Extending this to collaboration among multiple learners co-located in a shared synthetic environment may further augment learning outcomes.
- In general, usability of the virtual environment appears to enhance learning. However, optimizing the interface for usability does not necessarily optimize for learning. We have found instances in which changes to make the user interface more usable may actually impede learning. For example, in NewtonWorld to use size as an indication of a ball’s mass is facile for learners, but would reinforce a misconception that mass correlates with volume.

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4 Conclusion

An overarching theme in all our ScienceSpace research is to develop a theory of how multisensory “immersion” aids learning. In our virtual worlds, we can simultaneously provide learners with 3-D representations; multiple perspectives/frames of reference; a multimodal interface; simultaneous visual, auditory, and haptic feedback; and types of interaction unavailable in the real world (e.g., seeing through objects, flying like Superman). With careful design, these capabilities all can synthesize to create a profound sense of motivation and concentration conducive to mastering complex, abstract material. Studying this new type of learning experience to chart its strengths and its limits is an important frontier for cognitive science research and constructivist pedagogy [Dede, 1995].

Due to the huge profits of the videogame market and the entertainment industry, we expect that in less than a decade many of the capabilities of our expensive laboratory equipment will be “under the Christmas tree” for families, including impoverished households and homes in rural areas. This will potentially the largest installed base of sophisticated information technology for learning. Through work such as ScienceSpace, we hope to design intriguing, magical worlds for education accessible on these ubiquitous devices.

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