MaxwellWorld: Learning Complex Scientific Concepts via Immersion in Virtual Reality

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Abstract: Subjects such as electrostatics are difficult to teach in part because learners cannot draw analogies to personal experiences that provide metaphors. MaxwellWorld has been designed to allow students to explore electrostatic forces and fields, learn about the concept of electric potential, and "discover" the nature of electric flux. In formative assessments of MaxwellWorld's usability and learnability, students enjoyed learning about electric fields and cited the 3-D representations, the interactivity, the ability to navigate to multiple perspectives, and the use of color as characteristics that were important to their learning experience. Pre- and post-lesson evaluations show that students had a greater understanding of the distribution of forces in an electric field, as well as representations such as test charge traces and field lines. Our studies also indicate that the three-dimensional nature of VR aids with learning and that the virtual reality experience is more motivating for students than a comparable 2-D microworld.

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. Guided inquiry experiences that reveal the shortcomings of their current conceptual frameworks can help wean students from these erroneous beliefs.

To date, uses of information technology to apply these two 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. However, high-performance computing and communications capabilities create a new possibility [Dede 1995]. 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. The key features that virtual reality adds are:

- *immersion:* Learners develop the subjective impression that they are participating in a "world" comprehensive and realistic enough to induce the willing suspension of disbelief. Also, inside a head-mounted display the learner's is focused only on the virtual environment without the distractions presented in many other types of educational environments.
- *telepresence:* Geographically remote learners can experience a simultaneous sense of presence in a shared virtual environment.
- *multisensory stimulation:* 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, potentially deepening learning and recall.
- *motivation:* Learners are intrigued by interactions with well designed immersive environments, inducing them to spend more time and concentration on a task [Bricken & Byrne 1993].

- *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.

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 that are useful in understanding scientific principles 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. Designers can heighten this saliency by using multisensory cues to convey multiple, simultaneous representations of relative speeds. Transducing data and abstract concepts (e.g., acceleration) into multisensory representations is also a powerful means of enhancing understanding. Under these conditions, learners may be willing to displace previous misconceptions with alternative, more accurate mental models.

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 [Dede, Salzman, & Loftin 1996]. 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 enables the study of molecular structures via a variety of representations, including quantum-level phenomena. This paper focuses on our design and early formative evaluation of MaxwellWorld.

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 Polhemus 3Ball™, a three-dimensional mouse.

Description of MaxwellWorld

MaxwellWorld allows students to explore electrostatic forces and fields, learn about the concept of electric potential, 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. Menus and a virtual hand are used for interaction in this world. Figures 1-3 present images of MaxwellWorld.

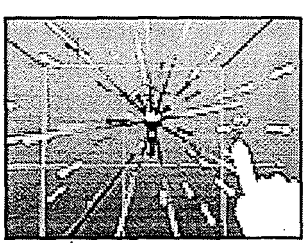

Figure 1. User exploring a field

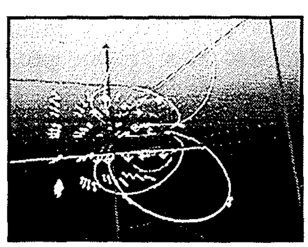

Figure 2. A dipole.

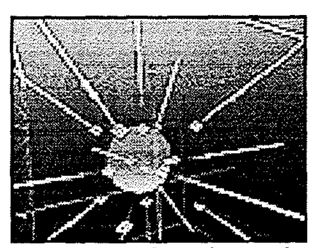

Figure 3. A Gaussian surface.

The menus in MaxwellWorld are attached to the left wrist just as a wristwatch would be (for left-handed users, the menu location can be on the right hand). This allows the menus to be removed from the field of view, but keeps them immediately accessible, since users always know where their hands are located. The virtual hand points to menu items, and the 3Ball button is depressed to execute a selection (just as in a two-dimensional interface the user manipulates the cursor by moving a mouse). For example, navigation in MaxwellWorld is accomplished by selecting the navigation mode via the menu, pointing the virtual hand in the desired direction, and depressing the 3Ball button.

Using their virtual hand, students can place both positive and negative charges of various relative magnitudes into the world. Once a charge configuration is established, the force on a positive test charge, electric field lines, potentials, surfaces of equipotential, and lines of electric flux through surfaces can all be instantiated, easily observed, and controlled interactively. For example, 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. A series of test charges can be "dropped" and used to visualize the nature of the electric field throughout a region.

In a like manner, an electric field line can be attached to the virtual hand. A student can then move his or her hand 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 world. Via the production of equipotential surfaces. By default, 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.

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.

Conducting Research on ScienceSpace

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 appear to have much more varied responses to 3-D, multimodal interfaces than to the standard 2-D graphical user interface with menus, windows, and mouse. Evaluating the multisensory dimensions of an immersive virtual world also adds an additional dimension of complexity to the assessment process.

As a result, we have developed elaborate, customized assessment methodologies for evaluating the usability and learnability of our ScienceSpace Worlds [Salzman, Dede, & Loftin 1995]. In addition, we are videotaping the hours of time we spend with each subject and studying these records for additional insights. Portions of our protocols center on calibrating and customizing the virtual world's interface to that particular learner.

Learner-centered formative evaluations are aimed at gathering qualitative insights that guide the refinement of the user interface [Soloway et al 1994]. We have identified four important dimensions along which to evaluate educational technologies:

- *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 progress through learning tasks within the environment and demonstrate that their learning can be applied to other domain-specific problems.
- *Usability vs. learning.* To begin to understand the relationship between usability and learning and to identify when the two goals may conflict. It is this interaction that creates the need to distinguish learner-centered design from user-centered design.
- *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 different alternatives of varying cost and complexity.

To date, we have performed two formative evaluations of MaxwellWorld. This careful evaluation strategy is generating data from which we are gaining a picture of how 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.

MaxwellWorld: Initial Formative Evaluation

In Summer, 1995, we assessed our initial version of MaxwellWorld as a tool for 1) remediating misconceptions about electric fields, and 2) teaching concepts with which students are unfamiliar. During the sessions, we administered one to three lessons centering on the construction and exploration of electric fields (electric force, superposition, test charges, field lines), electric potential (potential and kinetic energy, potential difference, work, potential vs. force), and the concept of flux through open and closed surfaces, leading up to Gauss's Law.

Our observations during the sessions, students' predictions and comments, usability questionnaires, interview feedback, and pre- and post-test knowledge assessments helped us to determine whether this early version of MaxwellWorld aided students in remediating any of their pre-existing misconceptions and in learning concepts with which they were unfamiliar. Additionally, these experiences aided us in developing modifications to MaxwellWorld to enhance learning outcomes.

The findings below are based on 14 high school students and 4 college students who participated in these evaluations. 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.

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

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

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

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

Although only four of the students used MaxwellWorld to learn about electric potential, all of them demonstrated that they could visualize the distribution of potential for basic charge arrangements, interpret the meaning of a distribution of potential, identify and interpret equipotential surfaces, relate potential difference and work, and describe some of the differences between electric force and electric potential. All were particularly surprised to see 1) 3-D representations of equipotential surfaces, particularly in the case of a bipole (two charges of the same size and magnitude), and 2) the varying nature of forces over an equipotential surface.

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

MaxwellWorld: 3-D Representations versus 2-D Representations

In January, 1996, we initiated an extended study designed to accomplish two goals: (1) 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, and (2) assess the usability and learnability of an enhanced version of MaxwellWorld with additional capabilities suggested by results from the initial formative evaluation above. This study is still in progress, so only early results are reported in this paper.

The portion of the study largely completed compares MaxwellWorld (MW) and EM Field (EMF) on the extent to which representational aspects of these simulations influence 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. Under these conditions limiting the functionality of the VR environment, the primary differences between the simulations were representational dimensionality (EMF's 2-D vs. MW's 3-D) and type (EMF's quantitative vs. MW's qualitative). The second phase of the study, now beginning, utilizes MaxwellWorld's full range of capabilities (including multisensory input) to ascertain the value these features add to the learning experience. Through this two-stage approach, we hope to separate the relative contributions of 3-D representation vs. multisensory stimulation as instrumental to the usability and learning potential of virtual reality. This strategy also enables measuring retention over longer spans of time than we previously have done.

14 high school students (12 males and 2 females) completed the first phase of this study. All students have had 1 1/2 years of high school physics and were recruited from a physics class in a local high school. Students' performance in their science and math classes was varied; their grades ranged from A through C (As and Bs were the norm). Although students were advanced in their knowledge of physics relative to the typical high school population, most remembered little about electric fields and electric potential upon joining this study—this confirms the limits of conventional approaches to teaching this type of scientific material. Both groups of students participated in two, two-hour learning experiences, with the lesson in each session lasting approximately one hour. Using comparable capabilities of EM Field and a limited version of MaxwellWorld (abbreviated MW_L to distinguish this from the full version of MaxwellWorld), the lessons focused on electric fields and electric potential, mirroring concepts covered in the initial formative evaluation.

Our preliminary outcomes from Stage One of the study support the following findings:

- Students in both the EMF and MW_L groups demonstrated a better overall understanding of the topics on the post-test than on the pre-test. However, students with a moderate knowledge of electrostatics at pre-test benefited less than students demonstrating little or no knowledge at pre-test. In addition, the more advanced students who had misconceptions appeared to have a difficult time overcoming them despite experiences in the virtual worlds. This suggests that these types of virtual experiences should be integrated with initial instruction to avoid forming misconceptions difficult to remediate later.

- Conceptual learning substantially improved for both groups. After the lessons, the MW_L students provided slightly better and more complete definitions of phenomena than the EMF students. On the post-test, both groups performed substantially better on 2-D dimensional sketches as a result of their learning experiences. The MW_L subjects did slightly better on 2-D sketches of the electric field, but slightly less well on 2-D sketches of electric potential.

- During the post-test, the MW_L group was better than the EMF group at describing the three-dimensional nature of electric fields, potential, and their respective representations. Despite the inherent three-dimensionality of the demonstration exercises (as well as our use of the terms "surface" and "plane" in the lessons), EMF students typically restricted answers to a single plane; drew lines when describing equipotential surfaces; and used terms such as "circle," "oval," and "line." In fact, only one of the seven students in the EMF group described the phenomena in a three-dimensional manner. In contrast, MW_L students described the space, using 3-D gestures and phrases such as "sphere," and "plane" when referring to equipotential surfaces.

- Overall, students described MW_L as easy to use, interesting, and informative. They especially liked the three-dimensional representations, the ability to see phenomena from multiple perspectives, and the interactivity of the system. Students described EMF as very easy to use, but somewhat boring. They found the simplicity of its graphics both a strength and a weakness.
- Students rated the representations used in MW_L as easier to understand than representations used in EMF. At the same time, student ratings and comments suggest that MW_L was less easy to use than EMF. Some learners had trouble using the 3-Ball and virtual hand, and others felt the responsiveness of the MW_L system was problematic at times.
- Students who used MW_L were more motivated than students who used EMF. MW_L was rated as more rewarding, stimulating, informative, and invigorating, than EMF. Additionally, MW_L students indicated that they found it easier to remain attentive throughout the sessions than EMF students.
- In terms of simulator sickness, several MW_L participants experienced slight headache and eyestrain during the first lesson. Symptoms were less noticeable during the second lesson. Interestingly, several students using EMF reported slight drowsiness during both lessons one and two and of slight headache during lesson one.
- Working with the students yielded insights into the nature of their misconceptions about electrostatic phenomena. For example, learners have a strong tendency to think of charges in an electric field independently and have trouble describing the nature of superpositional fields and potential between sets of charges. Experiences in both MW_L and EMF clearly helped students to think about this issue, but they still had some difficulty understanding regions between sets of charges. In addition, field line representations are notoriously difficult to comprehend. Even after use of EMF or MW_L, several students continued to have misconceptions about the meaning of a field lines, although most learners gained a greater understanding of this representational formalism. Upon concluding the lessons in either system, how the electric field influences charged objects and the relationship between potential and force were also not completely understood by some students. The second phase of our study will clarify which of these continuing misconceptions are remediated when the full power of the VR system is utilized, including features such as multisensory representation and the user experiencing phenomena from the perspective of a test charge.

Although the subject population is small, these results suggest that the three-dimensional nature of VR aids with learning and that the virtual reality experience is more motivating for students than comparable 2-D microworlds. Given that many capabilities of MaxwellWorld were suppressed in this study, these finding are a promising indication of VR's capabilities to enhance educational outcomes.

Lessons Learned to Date on Usability and Learnability

Based on lessons learned from all our ScienceSpace research studies, we are developing design heuristics, assessment methodologies, and insights generalizable to a wide range of educational environments. A few of these are briefly discussed below.

Challenges in Current Virtual Reality Interfaces

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

- 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. Delays in VR system response time can also be a factor with complex environments. Both of these problems are steadily improving as hardware technology advances.
- 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.

- Students exhibit noticeable individual differences in their interaction styles, abilities to interact with the 3-D environment, and susceptibility to simulator sickness.
- To help learners utilize educational virtual worlds, calibrating the display and virtual controls for each individual is important. Additionally, monitoring and systematically measuring simulator sickness is vital, as malaise signals interface problems and also can explain why a learner is having trouble with certain activities.
- Spreading lessons over multiple VR sessions appears to be more effective than covering many topics in a single session. For example, 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.

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; 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:

- Multisensory cues can engage learners, direct their attention to important behaviors and relationships, 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) can increase saliency for crucial features of both phenomena and traditional representations.
- 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.
- Learner motivation is high in virtual reality environments, even when novelty effects wear off. The inclusion of interactivity; constructivist pedagogy; and challenge, curiosity, fantasy, and beauty [Malone & Lepper 1984] all seem to augment students' interest and involvement.
- Initial experiences in working with students and teachers 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, as may features (such as a "Hall of Fame") that provide social recognition for learner achievements.
- In addition to pre- and post-test assessments of learning, continuous evaluation of progress through lessons are critical to diagnosing the strengths and weaknesses of the virtual worlds. We have found talk-aloud protocols employing a cycle of prediction-observation-comparison are highly effective for monitoring usability and learning.

Based on these early results, we feel strongly encouraged on the potential utility of VR for facilitating certain types of learning more effectively than any other pedagogical modality. Further information, including additional research studies, can be obtained from our website: http://www.virtual.gmu.edu

Next Steps in Our Research

As a near-term research initiative in all our ScienceSpace Worlds, including MaxwellWorld, we plan to experiment with collaborative learning among geographically remote users inhabiting a shared virtual context.

Collaboration among users' "avatars" in shared synthetic environments may support a wider range of pedagogical strategies (e.g., peer teaching, Vygotskian tutoring, apprenticeship) and may make VR environments more intriguing to students who are most motivated to learn when intellectual content is contextualized in a social setting. Important questions to be answered are the value of providing learners with graphically-generated bodies and the degree to which the fidelity of the graphical representation affects learning and interaction (here fidelity is not simply visual fidelity, but also the matching of real body motions to the animation of the graphical body). We also plan to investigate the effectiveness of group learning situations in which three students rotate roles among (1) using the headmounted display, (2) serving as external guide, and (3) participating as a reflective observer.

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 extend the amount of information conveyed to the learner through each sensory channel conveying different data. Little is known about how what level of redundancy in sensory input is optimal for learning and about how much information users 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. Virtual reality provides a good research environment for exploring these design issues.

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.

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Acknowledgments

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