Vol. 34, No. 3 September 2005

PLANETARIAN

Journal of the International Planetarium Society

Special Focus: Digital Domes and the Future of Planetariums.

Digital Full-Domes: The Future of Virtual Astronomy Education

Dr. Ka Chun Yu
Curator of Space Science
Denver Museum of Nature & Science
2001 Colorado Blvd.,
Denver, Colorado 80205 USA
kcyu@dmns.org

Abstract

Even simple concepts in astronomy are notoriously difficult for the general public to understand, since many ideas involve three-dimensional spatial positional relationships and orientations between astronomical objects. However much of the teaching materials used in astronomy education are 2D in nature. Digital video full-dome planetariums have the potential to bridge the comprehension gap, using 3D virtual simulations in immersive environments that not only provide spatial context but may enhance learning in ways not possible via other techniques.

Although digital video full-dome theaters have the potential for showing a wide range of content, debate continues on how appropriate they are for astronomy education [1]. Such debate is not new. More than twenty years ago, Charles Hagar decried the fact that planetariums displaying video within their domes were trying to compete against first class Hollywood productions, and failing at it [2]. Given the expense involved in converting to full-dome theaters and the work necessary to create new visitor programming, operators and managers at traditional optical-mechanical planetariums may wonder whether the positives outweigh the negatives when taking the digital plunge. Since the main focus of planetariums has historically been that of astronomy education, what are the educational benefits of a digital system over its analog counterpart? Is the new technology actually worth it from an astronomy instructional point of view?

Before addressing how digital domes can be of use, it must be acknowledged that astronomy is a subject that has historically been difficult to teach. Although U.S. education standards identify astronomy topics as being important for K—12 science literacy [3, 4], most college students including many preservice teachers retain misconceptions that are not easily changed by standard classroom instruction (e.g., [5-8]).

The difficulty of understanding astronomy is due in part to concepts involving geometries and orientations of celestial bodies in three dimensions. Students have to build conceptual knowledge about a three-dimensional (3D) physical space while being taught using two-dimensional (2D) textbook materials. Many educational researchers have therefore advocated the use of 3D models as being crucial for astronomy learning [9, 10].

A suite of technologies especially appropriate for creating representational 3D models of physical phenomenon are the artificial realities or virtual environments. Virtual environments (VEs) are computer-generated, 3D environments that a user can interact with and navigate through. A carefully constructed VE allow users to gain direct experience about a place or phenomenon that would otherwise be difficult or impossible to observe in real life. When astronomy VE software[1] is run immersively in a full-dome theater, the illusion of the artificial reality is further enhanced by the wrap-around projection that surrounds the user with imagery on all sides.. As the following review will show, the combination of VE and full-dome technologies result in a unique opportunity for astronomy instruction that is not possible in any other milieu.

Misconceptions in Astronomy

Many involved in astronomy education are aware of the video *A Private Universe*, which shows the broad scope of misconceptions involving explanations of the seasons and the phases of the Moon among Harvard graduates [13]. For those familiar with basic astronomy, it is hard to imagine how phases of the Moon can be so extraordinarily difficult for people to understand. But more than five decades of research have shown how pervasive such errors are, with the same mistaken notions concerning lunar phases appearing from grade school children to undergraduate teachers in training, and in every country where this topic has been studied (e.g., [14-23]). As a further indicator of how perplexing this concept is, techniques for teaching lunar phases have had mixed success. Many studies have post-instruction understanding rates far below 50% [5, 24-27].

Phases of the Moon is not the only subject that is difficult to teach. Astronomical misconceptions by children and adults have been studied for a medley of topics, including the shapes and nature of orbits, the scale of the solar system, the Sun, distances to the stars, the Milky Way, the Big Bang, gravity, and the shape of the Earth [21, 28-33].

Studies of children's common perceptions of the shape of the Earth are particularly revealing. Their misconceptions can be startling to those not familiar with the educational research literature. Children at the K-3 level have been found to have a diverse

This is the first of four invited articles on the special topic **Digital Domes and the Future of Planetariums**. This topic will conclude in the next issue of the *Planetarian*. To become more involved in shaping the digital future of our profession, please see Steve Tidey's Forum on page 40, and visit my Digital Frontiers column on page 53 of this issue. – Ed Lantz

1. Such as UniView from SCISS-American Museum of Natural History [11] or the Denver Museum of Nature and Science's Cosmic Atlas [12}

set of mental models for the shape of the Earth [19, 21, 34]. These include (Fig. 2) [a] a flat rectangular surface that people reside on; [b] a flattened round disc; [c] a hollow sphere inside of which is a flat surface where people dwell; [d] a sphere flattened at the top and bottom where people can live; [e] a dual Earth consisting of a flat inhabited surface and a round Earth that is up in the sky; and [f] a spherical Earth with a population over the entire surface. Only in the last model is the concept of gravity correct. In most of the other models, gravity is seen as a force with a single universal up and down direction.

These mental models give a hint to the thinking processes of schoolchildren. Their models are the result of views that *make sense to them*. In the case of the Earth, their fundamental axioms include: the ground is flat, and objects including the Earth will fall down if not supported. When children learn from authority that "The Earth is round," they incorporate this new fact into their pre-existing model. A child who initially starts with a flat, rectangular Earth in his mind will modify his model into a disc-shaped Earth. Stella Vosniadou [21, p. 230] points out that the "dual Earth" model – a round Earth floating above a flat ground plane – can be attributed to children being shown pictures of the round Earth floating in space. They synthesize this new element without actually discarding their old mental model of a flat Earth plane where people live.

Such results are consistent with *constructivist theory* in education [35, 36], which states that people are not merely blank slates who automatically take in the knowledge taught to them. Instead they actively construct knowledge: they build mental models based on past experiences and everyday observations, in addition to formal instruction. However once a model is constructed for a phenomenon, it is difficult to displace. Information from additional teaching can merge into the mental model, and further modify it, but the original framework is rarely thrown out entirely. Developing instruction to correct for tightly held misconceptions is therefore a difficult task. The teacher has to be aware of what alternative mental models students hold, and has to create a curriculum that directly addresses these misconceptions. In order for students to replace their old models with scientifically correct viewpoints, they must become dissatisfied with their original mental model. And for new concepts to take hold, scientifically valid concepts must be taught so that they appear intelligible, plausible, and fruitful enough to lead to new discoveries [35].

Since the main focus of planetariums has historically been that of astronomy education, what are the educational benefits of a digital system over its analog counterpart? Is the new technology actually worth it from an astronomy instructional point of view?

Three-Dimensional Astronomy Teaching

Traditional astronomy teaching is made even more difficult by the fact that much classroom instruction involves 2D pictures, charts, slides, and written descriptions in textbooks. For instance, most of the past research on teaching phases of the Moon have used 2D drawings and diagrams (e.g., [19, 20, 24, 25, 37]). It is usually up to the student to conceptualize 3D abstractions using 2D descriptions. Using hand-held physical models of the Moon can help [38], but generally, it is a difficult task to translate and orient oneself to the perspective of another Solar System object, and look back at the Earth.

Computer 3D modeling and visualizations have therefore been suggested as critically important tools for learning new astronomical concepts and correcting naive but non-scientific notions [9, 39]. A prime strength of

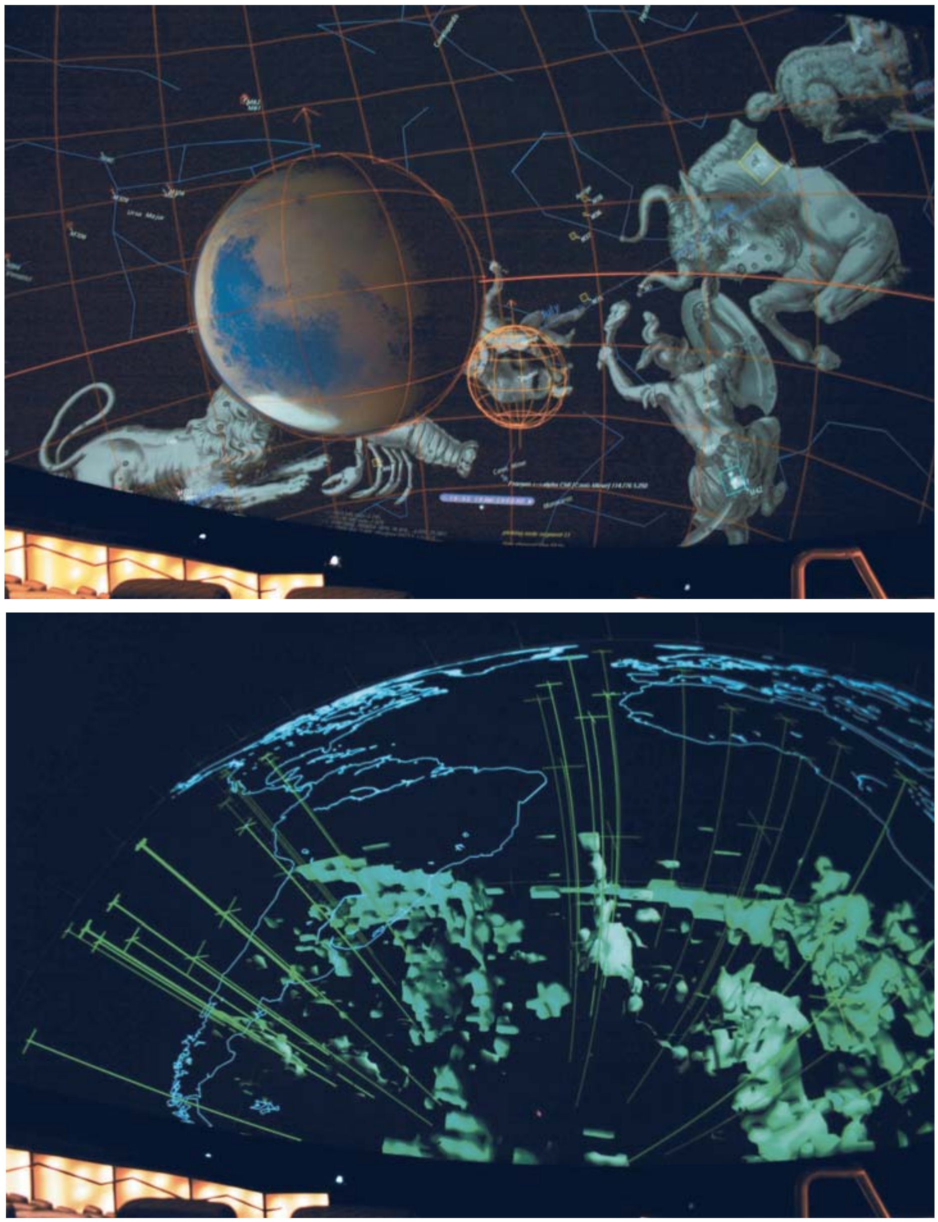

Figure 1: Virtual environment simulations running in the Gates Planetarium's real-time computer system at the Denver Museum of Nature & Science: (top) DMNS' Cosmic Atlas software showing the view above Phobos and Mars; (bottom) a 3D geological simulation of the Earth's mantle plumes displayed with an all-purpose model-loader.

computer-based simulation is the ability to change frames of reference. With immersive visualizations, users can have frames of reference that are external as well as internal to the simulated model. When a user is looking at the simulation from the outside, she has a global or *exocentric* perspective about its individual components. When a user is inside the model with its components all around her in an immersive display, this *egocentric* view reveals not just detail at the local level but makes the user feel as if she was actually in the space, as opposed to merely observing it. Having both perspectives can provide greater benefit than either alone [40]. The Virtual Solar System project at Indiana University and the University of Georgia allowed students to build their own solar system models in the computer, and gave them the ability to observe and change vantage points interactively. Those enrolled in classes using the software showed significant gains in learning of lunar phases and eclipses [10, 41, 42].

Another challenge in astronomy teaching concerns the distances to objects in space. Although the distance to objects in near Earth orbit (roughly 100 kilometers above ground) are well within most people's perceptual experience, most other measurements are vastly larger. The magnitude of distances to other planets, stars, or galaxies and their lack of any connection to personal experience is probably why the general public holds many misconceptions about astronomical sizes and distances [21, 31, 32].

Computer visualizations that encompass both small and large scales may be especially advantageous for understanding astronomical distances. For instance, the misconception that the space shuttle has visited the stars [31] or that the stars are located in the solar system [43], can be addressed by a virtual simulation that compares the scales of objects near the Earth to those elsewhere in the solar system and to distances to the stars. Side-by-side comparisons of human-scale spacecraft to large rocky planets and even larger gas giants would be difficult with physical models, but can be performed easily in a VE by "zooming out" to view increasingly larger objects. At least one study has taken advantage of the capability of VE software to switch frames of reference in such a way, and was able to correct students' notions about the shape and size of the Earth [44].

Finally most astronomical phenomena are also time-dependent. They require not just the understanding of spatial positions and orientations, but how those change over time. As a result, animated movies showing time-varying astronomical phenomena are now common in multimedia instructional materials that come with college astronomy textbooks [45]. Although such animations can show a physical phenomenon at different times, the perspective is usually fixed to a single vantage point. Only a VE simulation gives the user the freedom of moving to multiple perspectives in time as well as space.

The Psychology of Immersive VEs

The benefits of computer-generated reality systems in education have been studied by many researchers. For instance, Chris Dede and his collaborators have highlighted a number of advantages of VEs for learning complex spatial concepts, such as those often found in the physical sciences [46—48]. They include immersion which can increase student engagement; the ability to view 3D models from multiple frames of reference which can give additional insights into any phenomenon that occurs in a 3D physical space; and the increased student motivation from interactions with a well designed VE, even after the initial novelty has worn off.

Researchers have also discovered that visualizations of complicated data sets in immersive VEs can be more effective than the same visualizations in a non-immersive VE [49]. Test subjects using highly immersive VEs show better task performance and have higher satisfaction levels than those in non-immersive VEs [50].

Furthermore, large display systems (such as those found in digital domes) can increase the psychological sense of *presence* [51-54]. Presence (or "telepresence" as originally coined by Marvin Minsky twenty-five years ago [55]) is defined as the sense of "being there," where a user responds psychologically to a mediated environment as if that environment was local, not remote [56-58]. By using various psychological and physiological measures of presence, researchers have shown that increasing presence is correlated with an increase in attention [59], in the persuasiveness of the mediated message [60], improvements in memory and retention [61-63], and enhancements to task performance and navigation within a VE [54, 64]. Therefore any increase in presence can potentially increase the effectiveness of the content that is being taught [65].

Other parameters that increase the sense of presence happen to be suited perfectly for the new generation of full-dome theaters. These include improving image resolution [66, 67], widening the field-of-view (FOV) of the display [67-69], and enlarging the physical size of the display [70, 71]. Desney Tan and his collaborators have shown the importance of not just increasing the FOV, but increasing the dimensions of the display surface. In a series of papers, they showed that even when the same angular size of display is used, subjects using the physically larger display perform better in virtual navigation and spatial orientation [72-74].

The Future

Although traditional planetariums have been in wide use for many decades, studies of their effectiveness in astronomy teaching versus normal classroom instruction have had mixed results. Past research has shown improved performance in the planetarium [75-78], no difference between the two [79, 80], and better performance in the classroom [81, 82]. Because these studies involved traditional analog planetarium presentations

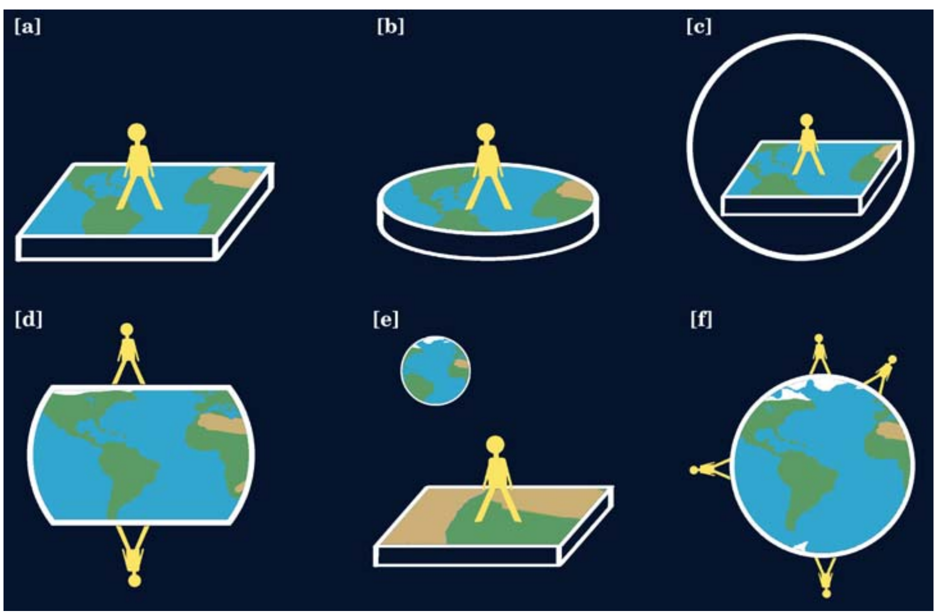

Figure 2: Examples of some of the most common notions of the shape of the Earth by schoolchildren. Only the last depiction is scientifically correct.

using mechanical star machines, their experimental subjects learned in an immersive dome, but did not benefit from any VE visualizations.

In recent years, advocates in the full-dome community have argued the qualitative advantages of the full-dome theaters, based on their large FOVs, and the educational potential of the technology. However only a handful of quantitative studies have looked at the effectiveness of domed displays (e.g., [68, 83]). A critical study at the Houston Museum of Natural Science showed significant improvement in comprehension from immersive full-dome 3D visualizations over 2D and non-immersive teaching methods [84]. But clearly more work needs to be done to quantify the advantages of immersive learning for astronomy education.

As suggested by the literature review above, immersive VEs combined with full-dome theaters may be a powerful tool for education. Not only astronomy but any other subject requiring complex spatial understanding may gain from visualization software running in such venues. If visual immersion also has quantifiable benefits, then full-dome theaters may offer instructional value that is not possible even if the same VE software were used in a "smart" classroom.

Digital full-domes are not usually regarded as true virtual reality (VR) systems[2]. However, they have far greater educational potential than traditional VR systems such as CAVEs and head-mounted displays. These mainstays of VR research are still expensive enough to be restricted to academic research settings and to industrial labs. They are also constrained by design the number of people they can accommodate at any one time. Although full-dome theaters are also expensive, they are built with large audiences in mind, and can be used for social and collaborative learning.

A growing number of full-dome theaters have been constructed at museums and science centers as part of planetarium renovations. Planetariums have built-in audiences numbering in the tens of millions [85], and as more institutions "go digital," the impact of full-domes on informal science education worldwide can be enormous. However the specific nature of this impact has to be properly quantified. (We at the Gates Planetarium have already started looking at research projects to study the best way to use immersive full-domes for teaching astronomy.) The techniques discovered must also be disseminated to planetarium educators, managers, and operators for them to be globally effective. Only by doing so can the successes from this new technology be leveraged for greater support and recognition for the entire full-dome community. Armand Spitz is oft quoted as calling the original Zeiss planetarium "the greatest teaching instrument ever invented" [86]. Digital video full-domes clearly have the promise to uphold that tradition.

2. Virtual reality is usually associated with — in addition to visual and aural immersion — stereoscopic displays, head-tracking sensors, and full user interactivity.

References

[1] Tidey, S. 2004, "Forum," *Planetarian*, 33(4), pp. 43-45

[2] Hagar, C. 1983, "Planetariums: *Star Wars* or Astronomy?" *Planetarian*, 12(3), pp. 14, 27

[3] American Association for the Advancement of Science, 1993, *Benchmarks for Science Literacy*, Oxford University Press

[4] National Research Council, 1996, *National Science Education Standards*, Washington, DC: National Academy of Sciences

[5] Schoon, K.J. 1995, "The origin and extent of alternative conceptions in the earth and space sciences: A survey of pre-service elementary teachers," *Journal of Elementary Science Education*, 7, pp. 27-46

[6] Atwood, R.C., & Atwood, V.A. 1996, "Preservice Elementary Teachers Conceptions of the Causes of the Seasons," *Journal of Research in Science Teaching*, 33, pp. 553-563

[7] Hufnagel, B., Slater, T., Deming, G., Adams, J., Lindell Adrian, R., Brick, C., & Zeilik, M. 2000, "Pre-course Results from the Astronomy Diagnostic Test," *Publications of the Astronomical Society of Australia*, 17(2), pp. 52-57

[8] Deming, G.L. 2002, "Results from the Astronomy Diagnostic Test National Project," *Astronomy Education Review*, 1(1), pp. 52-57

[9] Reynolds, M.D. 1990, *Two-dimensional versus three-dimensional conceptualization in astronomy education*, unpublished doctoral thesis, University of Florida, Gainesville

[10] Keating, T., Barnett, M., Barab, S.A., & Hay, K.E, 2002, "The Virtual Solar System Project: Developing Conceptual Understanding of Astronomical Concepts Through Building Three-Dimensional Models," *Journal of Science Education and Technology*, 11(3), pp. 261-275

[11] Klashed, S., Emmart, C., & Ynnerman, A. 2004, "Experiences from UniView: A Discussion on Real Time Standards," paper presented at the IPS 2004 Full-dome Standards Summit, Valencia, Spain, July 7, 2004

[12] Yu, K.C., & Jenkins, N.E. 2004, "Cosmic Atlas: A Real-Time Universe Simulation," *Bulletin of the American Astronomical Society*, 204, p. 7804

[13] Schneps, M.P. 1989, *A Private Universe* [Video], San Francisco, California: Astronomical Society of the Pacific

[14] Haupt, G.W. 1950, "First Grade Concepts of the Moon Part II: By Interview," *Science Education*, 34, pp. 224-234

[15] Kuethe, J.L. 1963, "Science concepts: A study of "sophisticated errors"," *Science Education*, 47, pp. 361-364

[16] Ault, C.R. 1984, "The everyday perspective of familiar astronomical events," *Journal of Geological Education*, 32, pp. 89-91

[17] Jones, B.L., Lynch, P.P., & Reesink, C. 1987, "Children's conceptions of the earth, sun, and moon," *International Journal of Science Education*, 9, pp. 43-53

[18] Treagust, D.F. 1988, "Development and use of diagnostic tests to evaluate students' misconceptions in science," *International Journal of Science Education*, 10, pp. 159-169

[19] Baxter, J. 1989, "Children's understanding of familiar astronomical events," *International Journal of Science Education*, 11, pp. 502-513

[20] Dai, M., & Capie, W. 1990, April, "Misconceptions held by the preservice teachers in Taiwan," paper presented at the annual meeting of the National Association of Research in Science Teaching, Atlanta, Georgia

[21] Vosniadou, S. 1991, "Designing curricula for conceptual restructuring: Lessons from the study of knowledge acquisition in astronomy," *Journal of Curriculum Studies*, 23, pp. 219-237

[22] Sadler, P.M. 1998, "Psychometric models of student conceptions in science: Reconciling qualitative studies and distractor-driven assessment instruments," *Journal of Research in Science Teaching*, 35, pp. 265-296

[23] Stahly, L.L., Krockover, G.H., & Shepardson, D.P. 1999, "Third Grade Students' Ideas about the Lunar Phases," *Journal of Research in Science Teaching*, 36(2), pp. 159-177

[24] Targan, D. 1988, *The assimilation and accommodation of concepts in astronomy*, unpublished doctoral dissertation, University of Minnesota, Minneapolis, Minnesota

[25] Callison, P.L., & Wright, E.L. 1993, April,

"The effect of teaching strategies using models on preservice elementary teachers conceptions about earth-sun-moon relationships," paper presented at the annual meeting of the National Association for Research in Science Teaching, Atlanta, Georgia
[26] Bisard, W.J., Aron, R.H., Francek, M.A., & Nelson, B.D. 1994, "Assessing selected physical science and earth science misconceptions of middle school through university preservice teachers," *Journal of College Science Teaching*, 24, pp. 38-42
[27] Schoon, K.J. 1992, "Students' alternative conceptions of earth and space," *Journal of Geological Education*, 40, pp. 209-214
[28] Duit, R. 2002, "Students' and Teachers' Conceptions and Science Education," Bibliography, Kiel University, Germany: Institute for Science Education, available online at http://www.ipn.unikiel.de/aktuell/stcse/stcse.html
[29] Bailey, J.M., & Slater, T.F. 2003, "A Review of Astronomy Education Research," *Astronomy Education Review*, 2(2), pp. 20-45
[30] Dunlop, J. 2000, "How Children Observe the Universe," *Publications of the Astronomical Society of Australia*, 17, pp. 194-206
[31] Sadler, P.M. 1992, *The Initial Knowledge State of High School Astronomy Students*, doctoral dissertation, Harvard University, Cambridge, Massachusetts
[32] Schoemer, J. 1994, *The Voyage Study: A Front-End Evaluation for a Scale Model of the Solar System*, unpublished master's thesis, University of Colorado, Boulder, Colorado
[33] Prather, E.E., Slater, T.F., & Offerdahl, E.G. 2002, "Hints of a Fundamental Misconception in Cosmology," *Astronomy Education Review*, 1, pp. 28-34
[34] Sneider, C.I., & Ohadi, M.M. 1998, "Unraveling Students Misconceptions about the Earth's Shape and Gravity," *Science Education*, 82(2), pp. 265-284
[35] Posner, G.J., Strike, K.A., Hewson, P.W., & Gertzog, W.A. 1982, "Accommodation of a scientific conception: Toward a theory of conceptual change," *Science Education*, 66(2), pp. 211-227
[36] Strike, K.A., & Posner, G.J. 1992, "A revisionist theory of conceptual change," in R.A. Duschl & R.J. Hamilton (Eds.), *Philosophy of Science, Cognitive Psychology and Educational Theory and Practice*, Albany, New york: State University of New York Press, pp. 147-176
[37] Nussbaum, J. 1979, "Children's conceptions of the earth as a cosmic body: A cross age study," *Science Education*, 63, pp. 83-93
[38] Trundle, K.C., Atwood, R.K., & Christopher, J.E., 2002, "Preservice Elementary Teachers' Conceptions of Moon Phases before and after Instruction," *Journal of Research in Science Teaching*, 39, pp. 633-658
[39] Parker, J., & Heywood, D. 1998, "The Earth and beyond: developing primary teachers' understanding of basic astronomical events," *International Journal of Science Education*, 20(5), pp. 503-520
[40] Salzman, M.C., Dede, C., Bowen Loftin, R., & Chen, J. 1999, "A Model for Understanding How Virtual Reality Aids Complex Conceptual Learning," *Presence: Teleoperators and Virtual Environments*, 8(3), pp. 293-316
[41] Barab, S.A., Hay, K.E., Squire, K., Barnett, M., Schmidt, R., Karrigan, K., Yamagata-Lynch, L., & Johnson, C. 2000a, "Virtual Solar System Project: Developing Scientific Understanding through Model Building," *Journal of Research in Science Education and Technology*, 9, pp. 7-26
[42] Barab, S.A., Hay, K.E., Barnett, M., & Keating, T. 2000b, "Virtual Solar System Project: Building Understanding through Model Building," *Journal of Research in Science Teaching*, 37(7), pp. 719-756
[43] Keane-Timberlake, S. 1996, "Front-end summary: Sort the Universe," Chicago, Illinois: Adler Planetarium
[44] Moher, T., Johnson, A., Ohlsson, S., & Gillingham, M. 1999, "Bridging Strategies for VR-Based Learning," *CHI' 99: Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 536-543
[45] Pasachoff, J.M. 1996, "Textbooks and Electronic Media," in J.A. Percy (Ed.), *Astronomy Education: Current Developments, Future Coordination*, Astronomical Society of the Pacific Conference Series, Vol. 89, proceedings of the ASP symposium held in College Park, Maryland, June 24-25 1994, pp. 66-72
[46] Dede, C., Salzman, M.C., & Bowen Loftin, R. 1996, "ScienceSpace: Virtual Realities for Learning Complex and Abstract Scientific Concepts," in *Proceedings of IEEE Virtual Reality Annual International Symposium*, New York: IEEE Press, pp. 246-253
[47] Salzman, M.C., Dede, C., Bowen Loftin, R., & Ash, K. 1998, "VR's Frames of Reference: A Visualization Technique for Mastering Abstract Information Spaces," *Proceedings of the Third International Conference on Learning Sciences*, pp. 249-255
[48] Dede, C., Salzman, M.C., Bowen Loftin, R., & Sprague, D. 1999, "Multisensory Immersion as a Modeling Environment for Learning Complex Scientific Concepts," in N. Roberts, W. Feurzeig, & B. Hunter (Eds.), *Computer Modeling and Simulation in Science Education*, Springer-Verlag, pp. 282-319
[49] Bowman, D.A., & Raja, D. 2004, "A Method for Quantifying the Benefits of Immersion Using the CAVE," *Presence-Connect*, 4(2), online journal available at www.presence-connect.com
[50] Raja, D., Bowman, D.A., Lucas, J., & North, C. 2004, "Exploring the Benefits of Immersion in Abstract Information Visualization," *Proceedings of the Immersive Projection Technology Workshop*
[51] Taylor, W. 1997 "Student Responses to Their Immersion in a Virtual Environment," presented at the Annual Meeting of the American Educational Research Association, March, 1997, Chicago, Illinois
[52] Lin, J.J.-W., Duh, H.B.L., Parker, D.E., Abi-Rached, H., & Furness T.A. 2002, "Effects of Field of View on Presence, Enjoyment, Memory, and Simulator Sickness in a Virtual Environment," *Proceedings of IEEE Virtual Reality 2002*, pp. 164-171
[53] Tan, D.S., Czerwinski, M., & Robertson, G. 2003a, "Women Go With the (Optical) Flow," *Proceedings of the Conference on Human Factors in Computing Systems*, April 5-10, 2003, Ft. Lauderdale, Florida, pp. 209-215
[54] Tyndiuk, F., Lespinet-Najib, V., Thomas, G., & Schlick, C. 2004, "Impact of Large Displays on Virtual Reality Task Performance," *Proceedings of the 3rd International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa*, November 3-5, 2004, Stellenbosch, South Africa, pp. 61-65
[55] Minsky, M. 1980, June, "Telepresence," *Omni*, pp. 4552
[56] Slater, M., & Usoh, M. 1993, "Presence in Immersive Virtual Environments," *Proceedings of IEEE VRAIS*, pp. 90-96
[57] Lombard, M., & Ditton, T. 1997, "At the

Heart of It All: The Concept of Presence," *Journal of Computer-Mediated Communication*, 3(2), available online at www.ascusc.org/jcmc/vol3/issue2/lombard.html

[58] Freeman, J., Lessiter, J., & IJsselsteijn, W. 2001, "An introduction to presence: A sense of being there in a mediated environment," *The Psychologist*, 14, pp. 190-194

[59] Darken, R.P., Bernatovich, D., Lawson, J., & Peterson, B. 1999, "Quantitative Measures of Presence in Virtual Environments: The Roles of Attention and Spatial Comprehension," *Cyberpsychology and Behavior*, 2(4), pp. 337-347

[60] Kim, T. 1996, *Effects of Presence on Memory and Persuasion*, unpublished doctoral dissertation, University of North Carolina, Chapel Hill, North Carolina

[61] Ditton, T.B. 1997, *The Unintentional Blending of Direct Experience and Mediated Experience: The Role of Enhanced Versus Limited Television Presentations*, unpublished doctoral dissertation, Temple University, Philadelphia, Pennsylvania

[62] Reeves, B., & Nass, C. 1996, *The Media Equation: How people treat computers, television, and new media like real people and places*, Cambridge: Cambridge University Pres, pp. 193-293

[63] Detenber, B.H., & Reeves, B. 1996, "A bio-informational theory of emotion: Motion and image size effects on viewers," *Journal of Communication*, 46(3), pp. 66-84

[64] Arthur, K. 2000, *Effects of field of view on performance with head-mounted displays*, unpublished doctoral dissertation, University of North Carolina, Chapel Hill, North Carolina

[65] Usoh, M., & Slater, "An Exploration of Immersive Virtual Environments," *Endeavour*, 19(1), pp. 34-38

[66] Duh, B.L., Lin, J.W., Kenyon, R.V., Parker, D.E., & Furness, T.A. III 1997, "Effects of Characteristics of Image Quality in an Immersive Environment," *Presence: Teleoperators and Virtual Environments*, 11(3), pp. 324-332

[67] Piantanida, T.P., Boman, D., Larimer, J., Gille, J., & Reed, C. 1992, "Studies of the field-of-view/resolution trade-off in virtual reality systems," *Human Vision, Visual Processing, and Digital Display III*, 1666, pp. 448-456

[68] Hatada, T., Sakata, H., & Kusaka, H. 1980, "Psychophysical Analysis of the "Sensation of Reality" Induced by a Visual Wide-Field Display," *SMPTE Journal*, 89, pp. 560-569

[69] Prothero, D., & Hoffman, H.G. 1995, "Widening the field-of-view increases the sense of presence in immersive virtual environments," Technical Report TR-95-2, Seattle,WA: University of Washington Human Interface Technology Laboratory, available online at www.hitl.washington.edu/publications/r-95-5

[70] Simmons, T. 2001, "What's the Optimum Computer Display Size?" *Ergonomics in Design*, Fall 2001, pp. 19-25

[71] Baudisch, P., Good, N., Bellotti, V., & Schraedley, P. 2002, "Keeping Things in Context: A Comparative Evaluation of Focus Plus Context Screens, Overviews, and Zooming," *CHI' 02: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Changing our World, Changing Ourselves*, April 20-25, 2002, Minneapolis, Minnesota, pp. 259-266

[72] Czerwinski, M., Tan, D.S., Robertson, G.G., 2002, "Women take a wider view," *CHI' 02: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Changing Our World, Changing Ourselves*, April 20-25, 2002, Minneapolis, Minnesota, pp. 195-202

[73] Tan, D.S., Gergle, D., Scupelli, P.G., & Pausch, R. 2003b, "Large Displays: With Similar Visual Angles, Larger Displays Improve Spatial Performance," *Proceedings of the Conference on Human Factors in Computing Systems*, April 5-10, 2003, Ft. Lauderdale, Florida, pp. 217-224

[74] Tan, D.S., Gergle, D., Scupelli, P.G., & Pausch, R. 2004, "Physically Large Displays Improve Path Integration in 3D Virtual Navigation Tasks," *Proceedings of the 2004 Conference on Human Factors in Computing Systems*, April 24-29, 2004, Vienna, Austria, pp. 439-446

[75] Wright, D.L.C. 1969, *Effectiveness of the planetarium and different methods of its utilization in teaching astronomy*, unpublished doctoral dissertation, University of Nebraska, Lincoln, Nebraska

[76] Bishop, J.E. 1980 *The development and testing of a participatory planetarium unit emphasizing projective astronomy concepts and utilizing the Karplus learning cycle, student model manipulation, and student drawing with eighth grade students*, unpublished doctoral dissertation, University of Akron, Akron, Ohio

[77] Sonntag, M.S. 1981 *An experimental study of teaching method, spatial orientation ability, and achievement in selected topics of positional astronomy*, unpublished doctoral dissertation, University of Colorado, Boulder, Colorado

[78] Mallon, G.L., & Bruce, M.H. 1982, "Student Achievement and Attitudes in Astronomy: An Experimental Comparison of Two Planetarium Programs," *Journal of Research in Science Teaching*, 19, pp. 53-61

[79] Rosemergy, J.C. 1967, *An experimental study of the effectiveness of a planetarium in teaching selected astronomical phenomena to sixth grade children*, unpublished doctoral dissertation, University of Michigan

[80] Dobson, H.D. 1983, *An experimental study of the effectiveness of the planetarium in teaching selected science concepts in the middle school*, unpublished doctoral dissertation, Pennsylvania State University

[81] Reed, G., & Campbell, J.R. 1972, "A Comparison of the Effectiveness of the Planetarium and the Classroom Chalkboard and Celestial Globe in the Teaching of Specific Astronomical Concepts," *School Science and Mathematics*, 72, pp. 368-374

[82] Twiest, M.G. 1989, *The attitudinal and cognitive effects of planetarium integration in teaching selected astronomical concepts to fourth, fifth, and sixth-grade students*, unpublished doctoral dissertation, University of Georgia

[83] Chen, J. 2002, *A Virtual Environment System for the Comparative Study of Dome and HMD*, unpublished master's thesis, University of Houston, Houston, Texas

[84] Sumners, C., & Reiff, P. 2002, "Creating Full-Dome Experiences in the New Digital Planetarium," *Proceedings of the NASA Office of Space Science Education and Public Outreach Conference*, San Francisco: Astronomical Society of the Pacific Conference Series, pp. 155-159

[85] Petersen, M.C. 2004, "Tallying the World's Planetarium Attendance," 25 August, 2004, Loch Ness Productions, online document at www.lochness.com/pltref/attend.txt

[86] Abbatantuono, B.P. 1995, "Armand Spitz Seller of Stars," *Planetarian*, 24(1), pp. 14—22 ☆