The Round Earth Project—Collaborative VR for Conceptual Learning

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Using virtual reality in a project to help children understand the concept of a round versus flat earth produced statistically significant results in the formal test.

The concept of a round Earth isn't a simple one for children to acquire. Their everyday experience reinforces their deeply held notion that the Earth is flat. Told by adults that the Earth is round, they often react by constructing a mental model of the Earth as a pancake, or a terrarium-like structure with people living on the flat dirt layer inside, or even a dual model with a spherical Earth and a flat Earth coexisting simultaneously. In effect, children attempt to accommodate the new knowledge within the framework of their existing conceptual models. Unfortunately, holding tight to the features of those prior models inhibits fundamental conceptual change.

The Round Earth Project is a collaboration among researchers in computer science, education, and psychology. It investigates two alternative pedagogical strategies for teaching children that the Earth is spherical and the implications of that fact. One strategy, which we term the transformationalist approach, attempts to effect conceptual change by breaking down the children's prior models. In contrast, the selectionist strategy attempts to effect learning in an alternative setting (in our case, a small-diameter asteroid), free of preexisting biases, and to relate that learning back to the target domain—the Earth.

Virtual reality (VR) technologies support both pedagogical strategies. In the transformationalist approach, VR simulates the launching of a spacecraft from the Earth's surface and subsequent exploration within a fixed-height orbit. In the selectionist approach, VR simulates a small-diameter asteroid. Thus learners may walk on a body with a curved horizon, see objects appear from below the horizon, take a long walk around the entire globe, and come back to where they started. In both environments, distributed VR technologies provide a collaborative learning environment promoting positive interdependence among pairs of learners.

Initial pilot studies involved bringing children to the VR equipment in the laboratory. However, the actual studies bring the VR equipment into a local elementary school as part of an ongoing research program looking at the use of VR in conceptual learning for children.

VR and learning

Research in conceptual learning using VR is a relatively young field, but growing rapidly. In a recent report by the Institute for Defense Analysis, Christine Youngblut comprehensively surveyed work over the past few years in the area, citing approximately 50 VR-based learning applications and 35 studies that include desktop but exclude text-based virtual environments.[1]

Currently there exist very few VR-based learning environments designed for young children and only two multiuser virtual educational worlds: Virtual Physics at the University of Lancaster[2] and NICE (Narrative, Immersive, Constructionist/Collaborative Environments) at the University of Illinois at Chicago.[3] Other educational VR worlds such as the ScienceSpace[4] worlds are being extended to support multiple users. Collaboration encourages conversation, and conversation serves learning by presenting each learner with a slightly different view of the subject matter. Individuals must enrich their own representations in order to assimilate their partner's discourse. Conversation also improves evaluation. Rather than thinking aloud, the participants talk to each other.

NICE, an exploratory learning environment for children between the ages of 6 and 10, explicitly attempted to blend several learning and pedagogical themes within a single application. These themes—constructionism, exploratory learning, collaboration, and the primacy of narrative—reflect several of the most important educa-

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tional reform themes of the past three decades. The NICE garden was originally designed as an environment for young children to learn about the effects of sunlight and rainfall on plants, the "spontaneous" growth of weeds, the ability to recycle dead vegetation, and similar simple biological concepts that are part of a garden's life cycle. NICE supported real-time distributed collaboration with voice communication enabled by a real-time audio connection.

While NICE succeeded as an engaging social space and as a driver for collaborative VR, the cooperative learning was unstructured and undirected. As its successor, the Round Earth Project builds on the experience gained from NICE and seeks to remedy these deficiencies.

We focus on learning problems that meet four criteria:

1. The learning goal must be important. That is, it must be identified as a component of adult scientific (or other) literacy as reflected in national learning goals, standards, or benchmarks, such as Curriculum and Evaluation Standards for School Mathematics by the National Council of Teachers of Mathematics or Science for all Americans: A Project 2061 Report on Literary Goals in Science, Mathematics, and Technology by the American Association for the Advancement of Science.
2. The learning goal must be hard. That is, it must be reflected in the literature of researchers and/or practitioners as difficult to effect and resistant to conventional pedagogical strategies.
3. The learning goal must be plausibly enhanced by the introduction of immersive VR technologies.
4. Finally, VR-based learning environments must be informed by contemporary research in the learning sciences and educational practice.

Young children believe the Earth is flat. More precisely, their mental model of the world separates sky and earth into two parallel layers, one above the other; the two directions up and down are absolute. Empirical studies have demonstrated that telling young children that the Earth is round doesn't cause them to replace their intuitive model with a spherical conception of the Earth. Instead, children assimilate the new information into their prior knowledge and conclude that the earth is flat and circular.[5-7] Conceptual models of the earth as a pancake shape, as a partially compressed ball, and even as a "terrarium" (spherical but hollow, with a hole in the top for sunlight and half filled with dirt upon which people reside) are common in children of this age group (5 to 10 years old).

Children's intuitive model of the Earth is consistent with, and strongly supported by, everyday experience. Discourse has little impact, not only because words like "round" are ambiguous but also because talk about the Earth is abstract and cannot compete with the vividness of looking upwards when looking at the sky or seeing the ocean with its straight horizon. Pictures have little impact because they require a complex mapping between experience and the 2D plane. To understand a picture of a person on a spherical body, the viewer must project himself or herself into the picture—a cognitive capability beyond very young children. The same is true of a 3D representation such as a globe. However, in VR the children can be immersed in the experience if walking on the spherical surface of a small planetary body such as an asteroid.

Teaching young children that the Earth is spherical makes a good match with our four criteria:

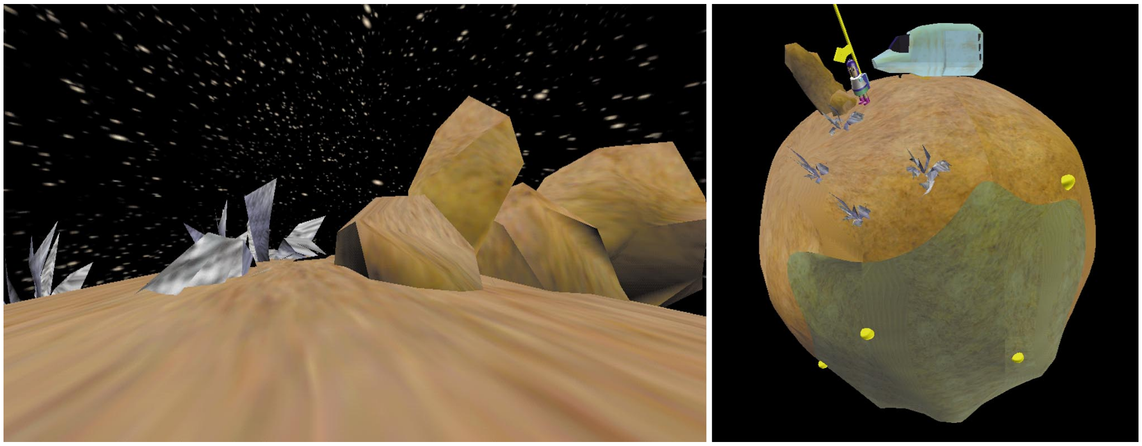
1. In AAAS Project 2061: Benchmarks for Science Literacy, fifth-grade graduates should know "things on or near the Earth are pulled toward it by the Earth's gravity" and "the Earth is approximately spherical in shape." Eighth-grade graduates should know "everything on or anywhere near the Earth is pulled toward the Earth's center by gravitational force." The spherical Earth is also reflected in local standards as part of the State of Illinois Learning Goal 13 ("Understand the fundamental concepts, principles, and interconnections of the life, physical, and earth/space sciences") and is a regular component of the local district's science curriculum for first- and second-grade students.
2. The existing literature by Vosniadou, Brewer, and Nussbaum discuss the difficulty of this learning problem.[5-7]
3. Immersive VR is well suited to giving a person the sense of walking on a spherical object with small diameter, seeing objects appear from below the horizon, and returning to the starting point after circumnavigating the sphere.
4. The environments designed in this project emphasize role differentiation with positive interdependence and collaborative learning.[8]

Deep learning

Underneath the extensive systems of domain-specific knowledge that a person brings to bear on problems and situations, there exist organizing concepts—fundamental ideas—that influence how a person conceptualizes both direct experience and discourse within that domain. Such deep ideas form the axiomatic core of entire systems of knowledge.[9,10] When experience or discourse attempts to communicate a deep idea both different from and more fundamental than the learner's existing ideas, a paradox occurs. Although the intent is to replace the learner's existing ideas, those existing ideas are the learner's only tools by which to acquire the new idea.

If this learning paradox is real, then how does anyone ever learn anything new? Our approach to this question distinguishes between transformationalist and selectionist explanations of cognitive change. The transformationalist account assumes that operations on prior knowledge create new knowledge. Prior knowledge serves as raw material, and the new knowledge results from generalization, specialization, or some other cognitive operator applied to the raw material.

The selectionist account of cognitive change assumes that a new understanding of a domain or phenomenon begins by establishing an alternative cognitive starting point—an idea or concept is established outside the



1 In the asteroid world, the astronaut explores the surface, collecting fuel cells as guided by mission control. The left image shows what the astronaut sees on the asteroid's surface. The right image shows the mission control view for the asteroid world, including the astronaut's avatar.

learner's existing system of domain knowledge. Initially such an alternative representation might be rudimentary and hence dominated by the prior well-established representation. However, over time all available representations compete and a representation that proves useful in dealing with certain types of situations or problems gradually gains strength and may even displace the previous representation.

The selectionist framework suggests a particular instructional strategy for supporting deep conceptual learning—fundamental ideas that contrast with the learner's current ideas need to be established on their own terms before they are brought into contact with the learner's prior ideas. VR, we believe, provides a powerful tool in helping to create such alternative cognitive starting points. We can also use VR to juxtapose and switch between multiple interlinked representations of the same experience. Our natural tendency in assimilating new information is that each facet of reality tends to be conceptualized in only one way, within a single perspective. Impasses on simple problems occur because the thinker assimilates or subsumes the problem under a prior conceptualization that doesn't support the solution. Switching representations is difficult, but deep learning may require precisely such shifts between alternative representations.

While we believe it's crucial to construct these alternative mental representations, our overall strategy requires a second step. The alternative representations must be brought into contact with the learner's prior knowledge of the domain and absorb or subsume it. Unless learners bring their new experience on the asteroid into contact with the everyday experience of walking on a seemingly flat Earth, they don't reach the learning objective. The point is not just to know what it would be like to walk on a spherical planetary body, but to understand that the Earth is such a body. We call this second step *bridging activities*.

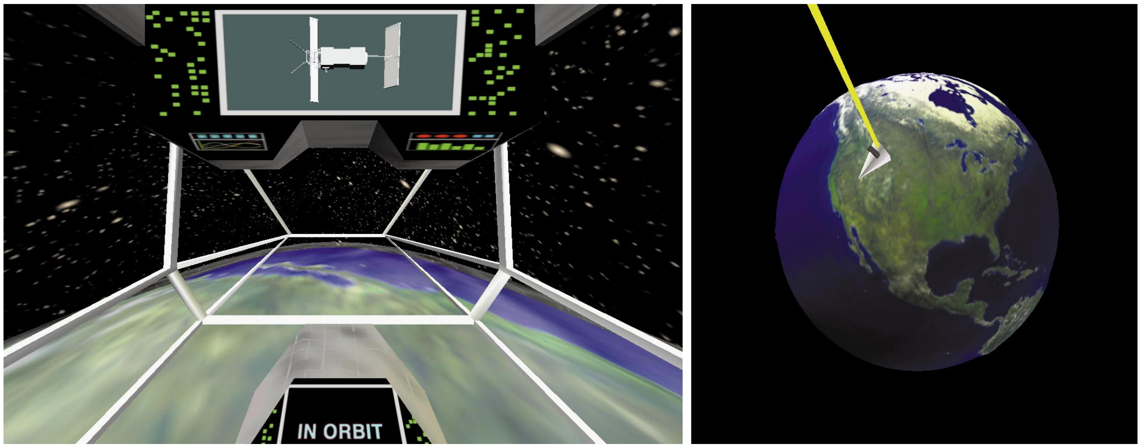
Asteroid world and Earth world

For the selectionist approach the children begin at an alternative cognitive starting point: a small asteroid. Here they can learn about walking around a spherical body different from the Earth. For the transformationalist approach the children begin on the Earth and attempt to transform their current flat Earth model into a spherical Earth model.

We wanted the children to see both the spherical representation of the planetary body as well as the flat view from the surface and integrate these two views. Because of this we made the world collaborative, with one child experiencing the world's surface and the other seeing the first child's avatar on the spherical world. We gave the kids a task to perform so that the child on the surface needed to move around the spherical body. This way one of the participants would often be upside down on the sphere but right side up on the surface. We wanted the collaborative task to foster positive interdependence, where neither child could perform the task alone; they had to cooperate and communicate with each other. Through this communication the children would need to reconcile their different views. Choosing simple controls meant little training time was involved, and the children could concentrate on the experience. We wanted to keep them engaged, giving them a long enough experience to grasp the concept but not so long that they became fatigued.

In both worlds the children must find 10 objects scattered around the planetary body. The two children play the roles of astronaut and mission control. The astronaut moves around the planetary body collecting each of the parts, guided by the other child. Mission control sees a spherical view of the planetary body, as if from an orbiting satellite, and can see the location of each of the 10 objects. Each child performs both roles during the experience to see both views. We expect that the children will successfully collect most or all of the objects in the allotted time. Even if they don't collect them all, they're told that they succeeded in their mission.

In the asteroid world, the two children find themselves marooned on the surface of a small asteroid. They need to retrieve 10 fuel cells from the surface and bring them back to the ship. The astronaut starts out in the airlock of the marooned spaceship and has 10 minutes to explore



2 **In the Earth world, the astronaut launches from Chicago up into orbit in the cockpit of a spaceship. The astronaut flies around the Earth collecting parts of a broken satellite, guided by mission control. The left image shows what the astronaut sees in orbit around the Earth. The right image shows the mission control view for the Earth world, including the astronaut's spaceship.**

the surface in search of the fuel cells. The child can carry up to four cells, then must return to the ship to drop them off. Mission control sees the astronaut as a person in a spacesuit walking on the surface of the asteroid.

After 10 minutes, the astronaut automatically teleports back to the ship. The children then switch roles. When both have had their time on the surface, they're told that they successfully completed their mission. They both stand in front of the ImmersaDesk to see their spaceship lift off from the surface of the asteroid and begin the journey home. See Figure 1.

In the Earth world, the two children must retrieve 10 parts from a broken satellite scattered in orbit around the Earth and bring them back for reassembly. The astronaut sits in the command chair of a spaceship on a launching pad surrounded by skyscrapers in downtown Chicago. Since our students live in Chicago, this gives them a familiar starting point on a very flat-looking Earth. As the engines roar, the astronaut is launched into space. The astronaut sees the buildings, then the city, then the Earth fall away as he or she rises into orbit to see an Earth with a curved horizon. Once in orbit the astronaut maneuvers the ship close to the satellite parts to retrieve them. Mission control sees the astronaut's pointy space capsule flying over the Earth's surface.

After 10 minutes the autopilot engages, maneuvers the ship back over the city of Chicago, and lands the ship back on the launch pad. The children then switch roles. When both have had their time in orbit, they're told that they successfully completed their mission. They both stand in front of the ImmersaDesk to see the reconstructed satellite. See Figure 2.

Pilot studies

To date, we've conducted three pilot studies leading up to the first formal study. The first pilot study consisted of four pairs of children, looking primarily at interface and usability issues in the two worlds. The second pilot study consisted of eight pairs of children, concentrating on learning in the two worlds, the effectiveness of the bridging activities, and the ability of the pre- and post-testing to reflect change in the children's models. These led to changes in our procedures. A third pilot study of five pairs of children in the asteroid world evaluated our modified design. At this point we felt prepared to undertake the first actual study, which consisted of 14 pairs of children.

For the pilot studies, the astronaut stood in a standard 10-foot Cave Automatic Virtual Environment (CAVE) with three walls and one floor. The astronaut wore a pair of stereo liquid crystal display (LCD) shutter glasses that also contained a position sensor for the Flock of Birds tracker and carried the standard CAVE wand—a six-degrees-of-freedom mouse with three buttons and an isometric thumb-controlled joystick. The astronaut's speech was picked up via an ambient microphone mounted on the top of the CAVE's front wall. Audio from the application and from mission control were mixed and sent through the CAVE's speakers. A low-light color charge-coupled device (CCD) camera mounted outside the entrance to the CAVE sent the image of the astronaut and the front CAVE screen into the computer for the ImmersaDesk and into a video cassette recorder (VCR) for recording.

The child acting as mission control stood at an ImmersaDesk. Mission control also wore a pair of LCD shutter glasses, but no head tracker. We did this so that the 3D image of the spherical planet would always remain completely on the screen, no matter how active the child became. The joystick served to spin the world, which could be turned completely around horizontally with limited tilt. This let mission control keep the astronaut in view at all times, but left the astronaut positioned right side up in the northern hemisphere, sideways near the equator and upside down in the southern hemisphere.

The camera image from the CAVE was sent into the ImmersaDesk and placed on the screen. A head-worn microphone picked up mission control's speech. Audio from the application and from the astronaut were mixed and sent through the ImmersaDesk's two speakers. A low-light color CCD camera mounted behind mission control sent the image of the child to the VCR for recording. Audio from both the CAVE and ImmersaDesk microphones also went to the VCR.

Two adult guides helped the children at the CAVE and ImmersaDesk. Initially, the guides simply helped with the equipment and the initial setup of the task, though their role became larger as the pilot studies continued. We also modified the bridging activities as the pilot studies progressed. We describe these changes and other issues the pilot studies raised in the next section.

The children for the pilot studies came from a small urban Chicago public school with which one of the team members had a previous relationship. This element of trust was very important, as we would be moving the children from the school to our lab for the VR experience. The third-grade students at this school scored significantly below the state and district averages in reading and math, and below the state average in writing. The first pilot study included the children of the teachers and administrators at the school, allowing us to familiarize their parents with our procedures. The second and third pilot studies included summer school students who did not pass the Iowa Test of Basic Skills Grade 3 exam. This group seemed like good candidates for an alternative learning experience.

Pilot study 1

The first pilot study with four pairs of children showed us several things about the usability of both the asteroid world and the Earth world. As with the NICE studies, the LCD shutter glasses were too big for small children. The only satisfactory solution we have found is to tie the glasses on. Initially the asteroid world astronaut would reach down to physically pick up the fuel cell, while the Earth world astronaut would only have to pilot his spaceship close enough to the satellite part before it was grabbed automatically. The Earth world children had a much easier time than those on the asteroid world, so we replaced the realistic asteroid world interface with automatic grabbing when the astronaut got close enough to the cell. This let the astronaut kids concentrate on the important task of moving about the asteroid rather than on the unimportant skill of picking up fuel cells.

We also simplified the navigation for the astronaut children in both worlds. From using the analog joystick to move about the asteroid, they went to using the three buttons to perform turn left, move forward, turn right—easier for small hands to control. We also enlarged the representations of the astronaut in the mission control view to eight times their actual size to make the direction the astronaut was facing more obvious. Once we made these changes, the children used the VR technology very effectively, and the application remained virtually unchanged for the rest of the studies.

Pilot study 2

A great deal of component knowledge is subsumed under the rubric of "knowing that the Earth is round." We prepared a 16-item questionnaire adapted from published questions used in earlier studies of children's models of Earth[5-7] designed to probe for understanding of the following four concepts:

1. The Earth is (roughly) spherical in shape.
2. There is no absolute up or down associated with a particular portion of the Earth.
3. The Earth's surface is continuous and can be circumnavigated.
4. The horizon is a curved edge that may partially or totally occlude objects on the other side (or in space).

We soon supplemented these with a 3D sculpting component using PlayDoh to get a better idea of the child's model(s).

The second pilot study involved four sets of two children in each of the worlds. We conducted individual oral pre-test interviews based on the questionnaire lasting 15 to 20 minutes at the school a day or two prior to their VR experience. We audiotaped these interviews for further review later.

The children were brought in pairs to our university campus, given a cover story describing the Earth world or asteroid world scenario, and briefly trained by an adult guide in using the VR apparatus. The children spent 10 minutes on each task twice, one child as mission control for 10 minutes, then astronaut for 10, then mission control for 10, then astronaut for 10. The guides only interfered when absolutely necessary, trying to keep the sense of immersion as strong as possible. The children became very engaged in the activity, and their sense of presence seemed high. Several said that they initially felt they would fall off the world if they walked over the nearby horizon, but once they walked over that horizon, they became comfortable moving over the surface.

The two distinct interfaces let us employ a tightly coupled jigsaw collaboration scheme, alternating each child between the two positively interdependent roles of astronaut and mission control. Most of the children actively talked to each other. Unfortunately, the children seemed almost too engaged in the task, focusing on the goal of collecting the fuel cells or satellite parts and only conversing on that specific topic. The children treated the experience as a big, enjoyable video game that they wanted to win.

We had thought that the mission control child would comment about the astronaut child being upside down and that the two children would need to integrate mission control's directions of "go up" and "go down" with the astronaut's directions of "go left" and "go right." The kids didn't talk about the other child being upside down and didn't use any of the available landmarks to aid in navigation. Most mission controllers eventually adopted a strategy of telling the astronaut to remain in place and turn in either direction until told to stop, then move forward. The mission control children rarely looked at the live video image of the astronaut in the CAVE. Instead they concentrated almost exclusively on the computer-generated image of the avatar moving around the sphere. The children focused intently on their goal of collecting the 10 objects, and the computer-generated spherical view helped them achieve that goal, while the live view did not.

When the two children completed the task, we brought them together in front of the ImmersaDesk for a bridging activity. An adult interviewer led them through a brief recounting of their experience using the mission controller view. Here we found that words such as horizon weren't in the children's vocabularies, making the bridging activities more difficult than expected. We reviewed and reinforced each of the four identified knowledge components in the context of the asteroid. In each case, we told the students that the same facts applied to the Earth as well, citing similarities and differences between the two celestial bodies. Immediately following the bridging activity, we brought the children to a different room and interviewed them separately using the same questionnaire. Following completion of the assessment, they returned to their school.

For each subject, we reviewed the audiotapes and written documents for evidence of learning in each of the four component knowledge areas. The results were disheartening. It became apparent from these questions that limited learning was reflected under either treatment. Among the kids who began with highly immature models of the Earth's shape (typically pancake shapes), all continued to hold to their naive models in the post-test interviews. The remaining children had indicated a belief in the sphericality of Earth in the pre-tests, but all fell short on one or more of the remaining knowledge components. Among these we found limited improvement in the relativity of up and down questions, and in the circumnavigability questions. Still, the robust outcome we had hoped for was obviously missing.

We stopped the second pilot study and considered the factors that may have led to our limited success. We identified numerous potential sources: the design of the application interfaces, novelty effects, learning and attention deficit disorders among our subject pool, social and communications difficulties among subject pairs, and more. We focused on what we believed were the two most important issues: over-engagement in the task at the expense of learning, and the failure to bridge learning about the asteroid to the subjects' mental models of Earth. We made some significant adjustments to our procedures, focusing for the time being exclusively on the asteroid world. Since the children seemed quite able to use the VR hardware and complete the task, we needed some way for them to focus less on the task and more on the concepts we wanted them to learn.

Pilot study 3

For the third pilot study with five pairs of children we modified our approach in several ways. Instead of a short training time with the guides focusing exclusively on the VR hardware, we now also used this initial time to point out features of the landscape. The guides gave each child an individual five-minute introduction to the astronaut view and a similar introduction to the mission control view, then introduced the collaborative task. The guide showed that if you kept going in the same direction you would return to where you started and that objects appeared top-first over the horizon.

Since the introductory time was increased, the children spent only 10 minutes in each role, rather than two sets of 10 as in the previous study. While walking the children between the CAVE and the ImmersaDesk, the guides reinforced the concepts brought up during the training session. The guides also tried to direct the attention of mission control to the video window when appropriate "right side up in the video" and "upside down on the sphere" situations appeared.

The children showed little consistency between their 2D and 3D models, often appearing to maintain separate-but-equal representations.

Most importantly, the bridging activities changed from a group debriefing in front of the ImmersaDesk to individual guided inquiry using a physical globe of the Earth and a Styrofoam model of the asteroid. This focused on reminding the subjects of what they had experienced, how their experiences demonstrated the target knowledge components, and how that same knowledge applied to the Earth. While the ImmersaDesk allowed mission control to see the astronaut moving over the surface of the sphere, the physical models allowed more direct manipulation and interaction between the instructor and the student with the model. The instructor could now position a small astronaut figure at any point on the sphere and manipulate the sphere's orientation.

We focused on a detailed analysis of individual subjects' protocols. This analysis was complicated by the fact that few instances of complete, fundamental changes in conceptual models occurred among subjects. Instead, we saw some subjects holding strongly to their initial models, some who appeared to demonstrate temporary effective learning during the experiment that wasn't reflected the next day, and some who appeared to reflect persistent learning of some, but rarely all, of the target knowledge components.

One obvious outcome of the study was the sensitivity of the subjects' responses depending on the dimensionality of the media. The children showed little consistency between their 2D and 3D models, often appearing to maintain simultaneous separate-but-equal representations. Children who demonstrated effective learning when asked to interact with 3D physical models would often revert to flat Earth models when asked to reason on the basis of 2D drawings.

Results of the three pilot studies

Simulator sickness didn't pose a significant problem during the pilot studies. In all of the studies, one child reported dizziness during the study, and that child refused to leave the CAVE. Another child expressed concern over sickness prior to the experience, but reported no difficulties during the experiment.

These three pilot studies with 34 children showed us that the children could use the VR equipment effectively. They were strongly engaged by the nominal tasks, sometimes to the detriment of the target learning, treating the experience like a video game to win rather than a possible source of learning. The children actively communicated with each other, though again on very task-specific topics. We were encouraged to see clear instances of learning related to specific knowledge components of the target concept. For those subjects who

3 Photograph of the ImmersaDesk and a stereo monitor deployed in a classroom at the elementary school. We placed the equipment back to back so each child could not see what the other saw.

appeared to undergo conceptual change, we believe that the VR experience effectively helped them establish an alternative cognitive starting point, as required by the selectionist learning model. These subjects found the asteroid a plausible reality and could use their experience to subsequently reason about how things might be on Earth.

But accepting the VR asteroid as plausible wasn't enough. Some subjects in the pilot studies who appeared to find the asteroid believable didn't successfully bridge their knowledge to the target domain. For subjects in pilot study 2, we believe that the fault lay in the abruptness of the intended bridging activity. Simply telling them that their new knowledge applied to Earth gave them no tools with which to bridge between two apparently dissimilar representations. The pilot study 3 subjects who succeeded in changing their concept of Earth did so, we believe, because the revised bridging procedures afforded them a chain of representations from source to target domain, with each new representation sufficiently similar to its predecessor for them to accept.

In spite of substantial cooperation by the school and the children, the difficulties in obtaining parental permissions, unanticipated absences, scheduling pullouts, and especially arranging transportation (liability concerns requiring us to employ unreliable and expensive taxi services) combined to make logistic support extremely time-consuming and expensive. Moreover, the process of running two pairs of children through the experiment typically required six adults for most of a working day.

You can find more details on the pilot studies elsewhere.[11,12]

Formal study

Because of the constraints in doing the experiments in the lab, we decided to conduct the actual studies inside the elementary school itself. When we were ready for the actual studies, the elementary school from the pilot studies was in the process of changing principals, so we had to look elsewhere. Because another of the team members had a long-standing relationship with an elementary school in his district, we again took advantage of a preexisting atmosphere of trust as the basis for working in close cooperation with the teachers and administration.

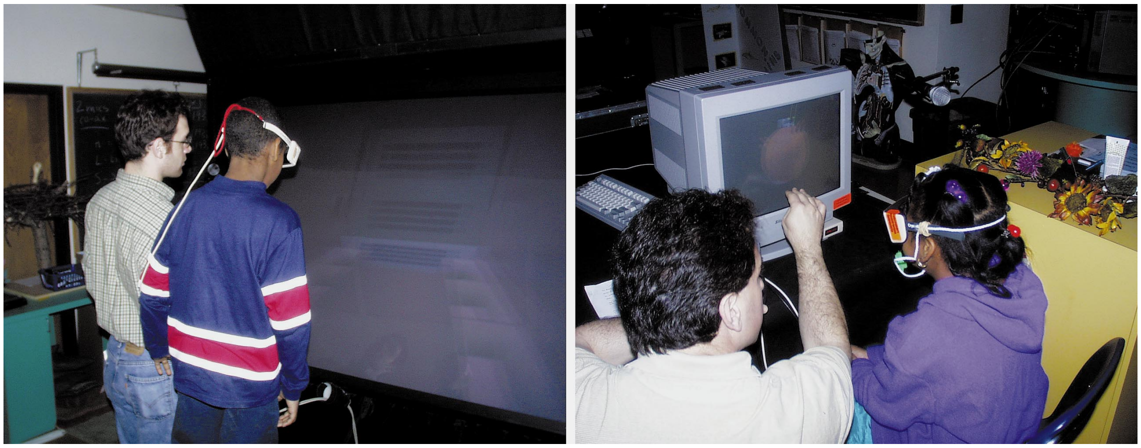
Before going into the school, we invited the principal and teachers from various grades to the lab. We wanted to show them the VR equipment, explain the current study and our long-term goals, and discuss how we could work together in the school.

This elementary school has a racially and economically diverse student body (29 percent African-American, 35 percent total minority enrollment) and faculty (28 percent minority), and offers diversity of subject mastery, as reflected by the Illinois Goal Assessment Program and Stanford-9 achievement tests administered at the school. While performing moderately above average as a school, it has significant representation in all performance quartiles. The school is also roughly average with respect to technology infusion, with about one computer for every five children, distributed both in classrooms and computer lab settings, and an orientation more toward computer literacy and technology education rather than conceptual learning.

We brought an ImmersaDesk and a stereo-capable monitor into a classroom in the school for two weeks, and conducted studies on the selectionist-based asteroid world. The ImmersaDesk was used for the astronaut view, giving the user a wide field of view on the surface, while the stereo monitor was used for mission control. The overall setup in the room appears in Figure 3 and the individual stations in Figure 4.

Since the mission control children in the pilot studies rarely used the live video feed from the astronaut's view, we removed that for this study. We again set up video cameras to monitor both children, but used that footage only for our analysis. We also modified the pre-test and post-test questions. The pretest now consisted of 18 questions spread over five topic areas: the sphericality and support of the Earth, the relativity of up and down, circumnavigation, occlusion, and egocentric versus exocentric perspectives. These questions were asked verbally, with 2D paper drawings, and using 3D PlayDoh models to minimize representational bias.

This school had 84 second graders in four classrooms. Since the students would be pulled out of class during the regular school day, we needed parental and teacher permission. Of the parental permission slips distributed to all the second-grade students two weeks ahead of time, 76 were returned. All of these children took the 20-minute pre-test, which took two days for all of them. We developed a simple scoring system and divided the children into three groups: the high group answered 14



4 Two children collaborating on the asteroid. The left photograph shows the astronaut at the ImmersaDesk about to leave the spaceship to search for fuel cells, while the right photograph shows mission control preparing to guide the astronaut on his quest.

or more correctly, the intermediate group answered 11 to 13 correctly, and the low group answered 10 or fewer correctly.

We chose the 29 children in the low group for the VR experience. From our previous experiments with the third-grade children at the pilot study school, we expected to have a larger subject population. Because we only had 14 pairs of children, we had them all experience the selectionist-based asteroid world. One week later randomly chosen pairs of these children came to the classroom, received their 10-minute guided tour of the worlds, received their mission, and then went through the 30-minute VR experience and the 10-minute bridging activities. The VR experience and the bridging activities were essentially the same as those in the third pilot study. On the next day they took the post-test.

During the experiment one child reported being dizzy at mission control, but wanted to continue. Several of the children reported being scared when they first stepped onto the asteroid in front of the ImmersaDesk, and one of the children was unable to continue.

The 22 children in the intermediate group became the quasi-control group. These children took the post-test without having the intervening VR experience. In the interest of fairness, following the post-tests the children in the intermediate and high groups had a chance to experience the VR worlds. It took us four days to give the experience to the treatment group and then an additional three days for all of the other children. The last day of the deployment coincided with the holiday sing at the school, where we demonstrated the VR equipment and worlds to the children's parents.

The performance of the treatment group increased from a mean of 7.3 correct answers on the pre-test to 12.9 correct answers on the post-test; the difference was signicant ($p < .05$). Because the pre-test and post-test contained identical questions, we were concerned that practice with the test itself might affect performance. The proper way to evaluate this concern would be to apply the same pre-test and post-test to a control sample drawn from the same population, in our case students in the low group. We couldn't do this because we applied the intervention to all of the students in the low group—both because we didn't want to withhold what we believed would be a valuable learning experience, and because dividing that relatively small sample in two would have made pre/post significance testing difficult.

In order to estimate the effect of test taking, we employed the quasi-control group. The performance of this group increased from a mean of 12.2 correct questions to 14.0 questions between pre-testing and post-testing. This difference was also significant ($p < .05$). While a formal comparison is impossible given the original differences between the two groups, the difference in the magnitude of the change between the two groups gives at least qualitative evidence that the intervention raised the lower group to roughly comparable performance with the intermediate group.

Four months later we returned to the school and conducted a delayed post-test with the original treatment group. The performance of the treatment group decreased slightly to 11.4 correct answers. Because we provided the treatment to the quasi-control group after they completed the post-test, they weren't candidates for delayed post-testing. Decreased levels of performance on delayed post-tests are the norm; what was important was that the learning effect had persisted. The difference between the pre-test and delayed post-test was still significant ($p < .01$), while the post-test and the delayed post-test didn't differ significantly from each other ($p > .05$).

Compared to the pilot studies, this study in the classroom went much faster and required fewer personnel. Our experience with taking VR hardware to conferences made the deployment to the school quite straightforward. The children seemed very excited by the experience. As word spread through the school, many children and teachers from other grades came by to see what was going on. A group of fourth graders lined up outside the classroom door at the end of one school day and, after assuring us that their parents knew they were staying late after school, stayed for two hours. Eventually they brought their teacher down and demonstrated the VR equipment and worlds to him. While we initially thought that the kids' familiarity with video games would make them jaded, our setup was favorably compared to various video game systems.

There was great interest among the kids and the teachers and principal in having us return to the school for future work, but winning hearts is not the same as winning minds. Adding more activity to an already crowded curriculum will garner long-term support only when we can convince the teachers that it will advance their goals of ensuring student success.

Conclusions and future work

We're continuing to analyze the results from this study, looking in more detail at individual children and performance on particular knowledge components. We are going to run several more experiments using the round Earth worlds. The first will compare the asteroid world to the Earth world. The second will investigate the relative effect of the VR experience and the bridging activities on learning. While we designed the two worlds to be collaborative, we also want to investigate letting a single user switch between the two representations at the ImmersaDesk or seeing both of them simultaneously. We also wish to further investigate the reasons for the differing success rates in the final pilot study versus the first actual study. Given the differences in the VR experience itself, the questionaire, and the location of the study, it's difficult to draw any meaningful conclusions at this time.

The Round Earth Project is part of a larger research effort to help prepare schools for the advent of advanced visualization technologies such as VR. We're trying to identify appropriate roles for those technologies within the context of learning and instructional theories, constructing and evaluating learning environments, and ultimately producing design support and working learner-centered applications for use in real elementary school settings.

Our focus is an investigation into the design, coordination, and effectiveness of multiple advanced visual representations of scientific phenomena in children's learning. You only have to open a science textbook to see the central role that multiple representation plays, but in order to benefit from multiple representations, the learner must be able to map between them. Many possible relationships exist between representations including exocentric versus endocentric, spatial displacement, scale, part-whole, and degrees of realism. Each type of relationship poses a different challenge for the learner to create the appropriate mapping. Under what conditions the benefit of these multiple representations offsets their increased cognitive load remains an open question. We believe that explicitly supporting the learner's task of constructing these mappings, either through discourse or explicitly embedding this mapping within the visualizations, will improve their effectiveness. We plan to develop both discourse-based and embedded support and compare their effectiveness in a variety of representational relationships. As part of this continuing work, we returned to Abraham Lincoln Elementary School and installed an ImmersaDesk, which will remain on site for the next two years. ■

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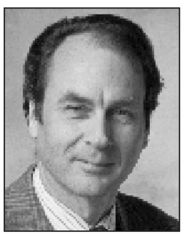

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