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ΣΥΝΟΨΗ

Στην εργασία αυτή παρουσιάζονται τα αποτελέσματα της χρήσης προσομοιώσεων σχετικά με την άρση των παρανοήσεων μαθητών Α' τάξης του Λυκείου για τις έννοιες της ταχύτητας και της επιτάχυνσης. Αρχικά προσδιορίζουμε και διερευνούμε τις αντιλήψεις και τις γνωστικές δυσκολίες που εμφανίζουν οι μαθητές στα τέσσερα έργα της έρευνας σχετικά με τις κινηματικές έννοιες. Διαπιστώνουμε ότι οι μαθητές εμφανίζονται να συγχέουν τις έννοιες ταχύτητας-θέσης, ταχύτητας-επιτάχυνσης και στιγμιαίας-μέσης ταχύτητας. Στη συνέχεια αξιολογούμε τη συμβολή της χρήσης προσομοιώσεων, που δημιουργήθηκαν μέσω του λογισμικού Interactive Physics, στην κατανόηση απλών κινηματικών φαινομένων και στη δημιουργία νοητικών αναπαραστάσεων. Η επεξεργασία των αποτελεσμάτων μας δείχνει ότι οι προσομοιώσεις βοηθούν τους μαθητές να ξεπεράσουν γνωστικές δυσκολίες, που οφείλονται στις παρανοήσεις τους σχετικά με τις έννοιες της στιγμιαίας ταχύτητας και επιτάχυνσης.

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Learning Science in Virtual Environments: The Interplay of Theory and Experience[1]

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ABSTRACT

Science is the connection between theory and experience. We use theory to explain our experiences and our experiences to construct theories. This article argues that virtual environments (VEs) help students learn science, by linking theory to experience, in three ways: By providing means to perceive and interact with phenomena normally beyond sense experience; by providing access to large amounts of information; by supporting students' ability to experiment with these phenomena in the same ways that scientists do. We describe a conceptual framework that is built around these three themes and which is guiding our research. Objects in VEs serve as "transducers" of phenomena that have no directly - perceptible properties. VEs are built from databases that can be as extensive as necessary. VEs can be the basis of complex and highly interactive simulations that foster conceptual change. We then illustrate how this conceptual framework has been used, by us and by others, to build VEs that help students understand science. We offer some data for their effectiveness and also draw attention to where we have made mistakes. We conclude by stressing the importance of conducting studies that examine how the unique properties of VEs can contribute to learning.

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
William Shakespeare.

O sweet spontaneous
earth how often ...
... has the naughty thumb
of science prodded
thy
beauty.
ee cummings

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INTRODUCTION

Science is the connection between theory and experience [1]. Theory helps us understand experience; experience lets us verify theory; science is the mechanism that drives both of these processes. Experience is limited by what our senses can detect directly and by our ability and desire to explain what our senses tell us. Theory is our best shot at explaining how the world really works, and often contradicts what our experience tells us. When things do not behave as our experience leads us to expect them to, theory can often tell us why. Yet theories have to be validated through experience, sometimes through observation, sometimes through experiments.

In this article we show how virtual environments (VEs) can help students learn science. It is our claim that VEs provide a more natural, intuitive link between theory and experience than is commonly the case in science classrooms, and thereby foster a better understanding of science. This is because VEs make it easier for students to conceptualize theory when it can be understood in terms of experiences they have had.

We begin with a short description of what we mean by VEs and how students explore them. Next, we examine how theory and experience differ. This leads to a description of the conceptual framework that is guiding our research into learning science in VEs. We then describe some completed studies that provide data relevant to our framework. We discuss our current research that involves the simulation of complex natural environments, and present some preliminary data. We end with conclusions about the role of VEs in learning science.

VISITING A VIRTUAL ENVIRONMENT

In our research, a virtual environment is an immersive or a "desktop" environment, created using virtual reality technology. To visit an immersive VE, a student wears a helmet in which a stereoscopic display presents graphics that are rendered in real time by a computer. The graphics represent virtual objects in three dimensions. The helmet is equipped with a position tracker that is connected to the computer. As the student's head moves, its position is constantly sent to the computer which re-computes the images in the eyepieces. What the student sees therefore moves in the visual field relative to the point of gaze. The students may look around in the VE by turning their heads, just as in the real world. The students interact with objects in the VE using a number of devices. A "wand" – a joystick-like device which is also tracked in space – has buttons that allow certain operations such as "flying" and picking objects up, and which appears in the field of view as a hand. With a navigation cube, the subject sees a wire-frame cube in the virtual world and a hand. With the hand inside the cube, the subject is at rest. The hand's position and distance from the cube determines in which direction and how fast to fly.

The technology therefore affords more intuitive ways of interacting with the computer. With practice, the interface becomes almost entirely transparent to the user [2]. The overall effect is that the students experience a degree of "presence" - the belief that they are "in" the VE, not standing in the classroom with a helmet on their head. (For a more extensive discussion of presence, see [3, 4]).

Visiting a "desktop" VE is more conventional. The student interacts with the VE, built using Java 3D or VRML (Virtual Reality Modeling Language) tools, using a mouse to operate a graphical interface. This allows the student to fly through the environment and to visit the surface to perform tasks. When the VE also uses augmented reality (AR) techniques, students wear goggles that allow them to see the real world - for example a map on a table - with virtual and manipulable objects superimposed on it. Now that head and hand tracking are operating, a student can reach down and pick up pieces of the landscape the map represents, and examine them as 3D objects held in their hands [5].

EXPERIENCE, THEORY AND SCIENCE

Experience and theory differ in three important ways. First, observation that may contribute to experience is severely constrained by our senses. Lakoff & Johnson [6] argue persuasively that our physical and neurological make-up determine how we perceive and reason about the world. This "embodiment" of our perceptual and cognitive capabilities limits our experience and our ability to understand it. For example, we cannot directly experience objects or events that reflect or emit energy outside the visible spectrum. Our physical size places us in a world where elephants are big and sparrows are small. Nor can we, unaided, watch the workings of a cell, nor the movement of planets around the sun. Embodiment even exercises a powerful influence over the linguistic metaphors we use to describe the world and our actions in it (see also [7]).

By contrast, much of scientific theory is derived from or confirmed by observations of phenomena that are beyond the realm of direct experience. Newton's contributions to astronomical theory would not have been possible without the telescope, nor Crick and Watson's to biology without X-ray diffraction. The experience scientists have of the natural world is thus extended by technology. Just as artifacts in the learning-environment distribute cognitive load and help students think through problems [8-10], as calculators reduce the cognitive effort required for computation, so do telescopes, microscopes and cyclotrons act as scientists' "tools for thought". We will argue later that VEs, acting as "transducers", extend students' experiences in similar ways.

A second way in which theory differs from experience arises from the amount of information from which each is built. Experience arises from information available locally. For example, someone living in California might declare that grass is green. However, a person from Montreal might declare, with equal legitimacy, that grass is either green or brown, depending on the season. Explanations about the behavior and nature of grass would therefore be local and possibly at variance. Theory, on the other hand, must be applicable generally and account for the variable color of grass. Darwin's theories could not have come about had he not gathered information from all over the world and, particularly, had he not observed variations among finches on many of the Galapagos Islands. The development and confirmation of the "big bang" theory would not have been possible without thousands of observations of the stars and galaxies. Thus, the amount of information required to construct a robust theory is much more than that available to normal experience. We will argue that the amount of information available to students in a VE is potentially greater than that which is accessible, locally, through unaided observation.

Finally, theory differs from experience in that the former arises from creative and effortful thinking about information acquired in the ways we have just described. As Suchman [11] has shown, while "just plain folks" attempt to explain and generalize about their everyday experiences, they do not apply rigorous and planful analysis to what they observe. People's pre-scientific explanations of phenomena are usually neither derived from nor confirmed by application of scientific methods. But Einstein's contributions to relativity theory could not have occurred without his deep thinking about phenomena, and their validation could not have occurred without careful experimentation. Later, we will make the claim that, while VEs do not imbue students with the intellectual prowess of Einstein, they nonetheless support scientific reasoning about data.

Because theory and experience differ in these ways does not mean that people cannot account for their everyday experiences. Indeed, current theory about conceptual change in learning science [12, 13] supposes that students come to science classes with some perfectly logical (for them) explanations about how the world works. These explanations, however, have the general characteristics of being poorly articulated, internally inconsistent, and highly dependent on context. Despite these qualities, informal ideas often have tremendous explanatory power in the mind of the student [14-16].

Not to be confused with this kind of unsystematic thinking about phenomena are explanations based on metaphysical beliefs rather than observation. For example, past and contemporary societies, not subscribing to the western scientific view of the world, have perfectly reasonable accounts of phenomena. Lightning is Zeus' thunderbolt. AIDS is God's punishment for promiscuity. These explanations are dubbed "naïve", "alternative" or "pre-scientific" conceptions. They can be the starting point for learning experiences that can eventually lead to more accurate, scientific, conceptions of the world. The standard for accurate conceptions is, of course, scientific theory. Misconceptions arise when explanations based on experience are at variance with the theoretical description of the same phenomena and, more importantly, when predictions generate data, in theory-derived experiments, that are at variance with predictions made from experience alone. The purpose of our work is to design VEs that help students develop pre-scientific conceptions of the world, based on experience, into conceptions that conform to scientific theory. The best way for them to do this is to act like scientists, as we shall see.

There is an implication in all of this that scientific theory is "right" and that explanation based on experience is "wrong". This is not the case. For example, we do not believe that current theory is so complete and accurate that there is no more for us to discover about the world. On the other hand, we abhor, for the same reasons as [1, 17, 18], the anti-scientific rhetoric of some "post-modernists", who claim that all knowledge is subjective, that there is no objective reality, and that scientific theory is an illusion.

CONCEPTUAL FRAMEWORK

In the previous section, we proposed that misconceptions occur when explanations based on experience are at variance with descriptions and predictions based on scientific theory. Given our argument so far, this implies that misconceptions arise when students: 1) Lack the ability (or technology) to observe phenomena beyond those immediately available to their senses. 2) Have only limited and local information about phenomena. 3) Lack the skills and the tools, such as scientific reasoning, to build from data valid, internally coherent and generalizable theories. It follows that we should do the following to change students' pre-scientific conceptions to scientific ones:

1. Provide students with the tools to gather data lying outside their direct sense experience.
2. Provide access to all the information they need to understand phenomena in a scientifically accurate way.
3. Encourage and guide students in the use of rigorous and logical methods for doing good science.

Virtual Environments can accomplish all three of these goals.

Extending experience through transduction

A transducer is a device that amplifies human experience. It converts data that are not directly perceptible into a form that is. A marine depth sounder is a good example. It bounces a sound that we cannot hear off the bottom of the sea that we cannot see and displays the echo as either a number or a graphic on a screen which is meaningful to us.

A VE is a transducer. It extends our capability to see, hear and touch data that would normally be beyond the range of our senses. It can do this because every object in a VE is created from data in a database. This means that anything that can be described digitally can be seen, heard, touched and interacted with in a VE. Objects we can experience directly, like cats, clocks and cabbages, can of course be drawn in three dimensions and placed in a database, using a CAD package. But objects beyond our experience can also be digitized and stored as data. These include objects that are too small to see, like atoms [19], objects that have no perceptible form, like electromagnetic fields [20, 21], and objects that are simply inaccessible, like the sea floor [22]. Once digitized, all objects have equal status in the VE, regardless of their provenance. This means that, in a properly constructed

VE, students can sense and interact with objects that lie outside direct experience in exactly the same way that they can interact with representations of objects within the range of normal experience. And they can do so in the same way that scientists can using their transducers - telescopes, microscopes, cyclotrons.

We call the representation, as virtual objects, of objects and phenomena that have no perceptible form, "reification" [23]. Reification requires attention to scale, metaphor and the behavior of the object. When we reify an atom, for example, the objects we choose to represent protons, neutrons and electrons must be of sizes that afford convenient manipulation [19]. The student must be able to pick them up easily. So a virtual proton is a bit bigger than an orange. Similarly, reifying the laws of planetary motion in a virtual solar system [24] requires, again, that the virtual objects be easily manipulable. A virtual planet is also a bit bigger than an orange. In these examples, the student's virtual body is made much smaller or much larger than normal. (The first "scene" of Byrne's [19] atom-building VE places the student in the "shrinking room". The student throws a switch and special visual effects give the impression that the student is getting smaller, like Alice in Wonderland.)

Objects and processes that have no perceptible form can only be shown as virtual objects through metaphors. This raises two issues. First, what metaphor works best for the concept or principle and for the students? Winn, Hoffman & Osberg [25] observed students in grade seven (twelve- and thirteen-year-olds) struggling to select appropriate metaphors for VEs they were building themselves to illustrate biological cycles. By and large, reified objects were represented using common graphic conventions. Evaporation of water from a pond appeared as transparent blue arrows pointing to the sky. Fixed nitrogen appeared as small yellow spheres surrounding a large yellow sphere.

However, the selection of a metaphor is not always this straightforward. The second issue related to metaphors is the danger that they instill "reductive bias" [26]. By expressing a new concept with reference to a known one, metaphors reduce the difficulty of what has to be learned. The subsequent risk is that students will learn only the familiar metaphorical and simplified object, not the new concept that lies behind it. In our VE that simulates global warming [27], for example, students can manipulate the amount of green plant mass available to absorb carbon dioxide in the air. Our metaphor for this process is increasing or decreasing the number of trees in the VE. (Our intention was to link the greenhouse effect to the destruction of the rain forests.) We have observed, however, that this leads grade seven students to believe that global warming will go away if we simply plant more trees! Our metaphor grossly oversimplifies the problem and, instead of correcting a misconception, it creates one.

In sum, transduction, change of relative size of the student's body and well-chosen metaphors allow students in VEs to experience and manipulate phenomena normally inaccessible to them. To the extent that the construction, comprehension and confirmation of theory can be encouraged by these phenomena, VEs can contribute to learning science.

Providing access to extensive sources of information

Any VE can provide students with information they would not normally have. All of the VEs we have mentioned so far in fact do so. However, the great advantage of VEs for learning science is that they may draw from and provide access to vast databases and sophisticated simulation models that normally only scientists have access to. In this section, we describe our current work as an example.

PRISM (Puget Sound Regional Synthesis Model) is a project whose aim is to consolidate atmospheric, hydrological and oceanographic databases and models for the Puget Sound region of the state of Washington, USA [28]. Geographical Information Systems (GIS) databases exist for the region and are used extensively by atmospheric, earth and ocean scientists. Mathematical models that predict the weather, floods, landslides and tidal currents also exist. However, to date these databases and models are largely incompatible. PRISM's goal has been to make them work together seamlessly.

At the heart of PRISM is an integrated three-dimensional environmental model of the entire Puget Sound region. It stretches from Admiralty Inlet in the North to Olympia in the South (200 km.), from the Cascade watershed in the East to the Hood Canal basin in the West (100 km.), and from the upper atmosphere to the bottom of the sea. It is indeed a large volume! We are building VEs from PRISM databases and models to help students learn about the complex environmental interactions among atmospheric, terrestrial and maritime processes that it is now possible to simulate.

So far, we have built two VEs from PRISM data. The first is an immersive VE, Virtual Puget Sound (VPS). At the heart of VPS is Kawase's adaptation of the Princeton Oceanographic Model [29] that simulates water circulation, temperature and salinity (and therefore density) for Puget Sound. Students can move through the VE, above and below water, to visit various "stations" where they take a variety of measurements. They do this within a problem-solving scenario. As they work, they develop and refine their conceptions of the causes and effects of water movement in the ocean.

The second VE built from PRISM databases uses "desktop" VR and augmented reality (AR) technologies. The VE is basically a three-dimensional topographical model of Big Beef Creek (BBC), a watershed that flows into Hood Canal, one of the major inlets of Puget Sound. GIS layers can be added to the VE allowing students to observe and measure such things as landcover and properties of the soil. Again, students may fly through the model and visit points on the land surface, where they may make measurements and "look around" the landscape using 360° Quicktime VR scenes.

We will say more about these projects later. For now, let us simply remark that students' understanding of how water moves in the ocean, and how atmospheric and hydrological processes work in a watershed, is informed by the most complete set of data and models for the Puget Sound region available anywhere.

Experiencing VPS and BBC in VEs leads to some surprises. For example, common experience suggests that tidal currents move parallel to the surface of the water. However, the bathymetry of Puget Sound, and vertical overturn, caused when denser water moves over less dense water and sinks below it, means that currents move up and down as well as horizontally. The complex, complete and "theoretically correct" models and data allow students to experience the three-dimensional movement of currents as they "swim" in the VE.

Encouraging conceptual change

Windschitl & André [30], building on earlier work [16], describe four necessary conditions for conceptual change to occur: 1) The student must be dissatisfied with the current conception; 2) The new conception must be intelligible, otherwise it will be simply remembered rather than understood; 3) The new conception must be plausible within the student's epistemological framework, otherwise it will be rejected; 4) The new conception must be fruitful, leading to successful solutions of new problems. Windschitl & André also found empirical support for a fifth condition: 5) The learner must actively test elements of their new conceptions in problem-solving activities. We believe that these conditions reflect the more general pattern of scientific discovery and verification: 1) Experience through observation reveals inconsistencies with current theory; 2) A logical (intelligible) explanation (hypothesis) for the new data is put forward; 3) The explanation is consistent with the student's current theory; 4) The hypothesis is tested experimentally, and if necessary other hypotheses are tested, until the revised theory is validated allowing new problems to be solved; 5) The whole takes place with an active, problem-solving, experience. Applying these approaches fostering conceptual change leads to a method for learning that closely parallels how scientists do their work.

VEs make it possible for students to reason like scientists about what they observe and to reduce the discrepancy between explanations based on everyday experience and explanations based on theory. In a VE, a student may experience compelling confrontations between events that reflect theory and events predicted from common experience. For example, one model that runs in our Global Change VE [27] makes the greenhouse effect self-correcting. The assumption is that if the students do nothing to control air pollution, people will start to die off leading to global collapse. As the population declines and with it the economic status and demands of the survivors, the amount of greenhouse gases will go down over time bringing temperatures down. Our observations with middle school students show us that, by and large, the decline in temperature after about 200 years is inconsistent with their conception of global warming increasing over time. Guided discussion leads to the "global collapse theory" and to dissatisfaction with the conception that global warming will increase forever.

The global collapse theory is nonetheless intelligible. Students can understand the relations among air pollution, health, climatic change and economic viability. The theory is also plausible. It does not violate in any significant way currently-held views of how the world works. Students can therefore hypothesize that reducing air pollution will delay, maybe even prevent, global collapse. Re-running the model in the VE with reduced values for air pollution, and perhaps increased values for available green plant mass, will let them test and possibly confirm their hypothesis.

Performing these activities around a VE has many advantages. To begin with, students are "present" in the VE and experience it "first hand" [23]. Second, they use their own tools (a virtual thermometer, CO_2 meter, rain gauge and time machine) to gather their own data. The VE allows them therefore to construct their own understanding [31] by interacting with the VE in their own way. The sequence of events meets the requirements for conceptual change, described above, while paralleling the methods scientists use to build theory. As a result, it brings students' conceptions closer to scientifically accurate ones.

Section Summary

In this section, we have described the conceptual framework that guides our work. It is based on the argument that VEs can provide to students the tools, information and intellectual rigor that are not available when explaining how the world works on the basis of everyday experience. In the next section we briefly describe projects that illustrate the conceptual framework and provide some evidence that the assumptions it makes about VEs are valid.

EXAMPLES OF VEs DESIGNED TO TEACH SCIENCE

The following descriptions of selected VEs designed to teach science illustrate, to varying degrees, the features of our conceptual framework. With the exception of the first example, all of these VEs have been built in our laboratory. However, there are many other researchers doing exciting work in this field. We certainly do not claim to be the only ones! (More information about these VEs can be found at http://www.hitl.washington.edu by following the link to "Education". Where on-line versions or stills from the VEs exist, we note the URLs below).

ScienceSpace

The ScienceSpace project [20, 21] has produced three VEs: Newton World, where students interact with balls moving along an alley to learn Newton's laws of motion; Pauling World, where they work with large organic molecules; and Maxwell World, where students interact with an electromagnetic field. Maxwell World provides a fine example of reification and of extending students' experience beyond what is available through the senses. This VE allows students to place positive and negative charges into an electromagnetic field and observe the resulting lines of force, potentials and equipotential surfaces. As they move a test charge through the field with their finger, arrows show the magnitude and direction of the influence of the charge on the field. Dede and his colleagues reported that working in Maxwell World increased students' understanding of the phenomena embodied in the VE. The visualization and manipulation of objects - reifications of abstract processes - were a major contributing factor to developing this understanding.

In addition to reification. Maxwell World and Pauling World "shrink" the student to atomic size. This makes electrical charges and organic molecules easy to handle. There is no evidence that change of size confuses students or causes misconceptions. In Newton World, the ability to "become" one of the balls provides students with direct experience of how the forces described by Newton's Laws affect moving bodies. While none of the VEs in Science Space provides access to large databases, they nonetheless do draw on information that students would not normally have, such as the structures of complex organic molecules.

Also, all three VEs allow students to observe phenomena, construct hypotheses, and test them. For example, Newton World allows students to manipulate gravity and the mass of the balls. This can lead to students building scientific conceptions about how these and other factors interact to affect how bodies move. (Stills and movies of the ScienceSpace worlds can be viewed at http://www.virtual.gmu.edu).

Atom World

Byrne's [19] project had grade 11 students (sixteen- and seventeen-year-olds) construct atoms from subatomic particles by hand. A supply of electrons, protons and neutrons was available for them to use. They picked up and placed these in the right combinations to construct atoms. In addition, they could move levers to change electron spin and energy. If they did not perform these two tasks correctly, they could not add to the atom they are building.

Byrne's VE exemplifies reification and radical size changes. It also uses fairly conventional metaphors. A proton is reified as a three-dimensional cross, an electron as a rotating minus sign. When placed correctly, the electron changes into a semi-transparent shell around the nucleus. Atom World has a reasonably extensive database behind it, containing information about atomic structure, valence, etc. for atoms from hydrogen up to carbon in the periodic table. It, too, permits students to experiment with manipulating which particles to add and to change the spin and energy successive electrons have. However, it does not permit errors nor, therefore, the creation of "mutant" atoms from which students might also learn something about atomic theory. (A non-immersive version of this world that runs under Windows NT over the Web is available at http://www.imprintit.com by following links to "Products", "Atomic Kitchen").

Byrne demonstrated empirically that her VE improved students' conceptual understanding of how atoms are built, though not their recall of facts, relative to other instructional strategies. However, she also found that the key to the success of her VE was the interaction it permitted, not the fact that students were immersed in the VE. Students learning from Atom World performed no better than students learning in a non-immersive interactive desktop version of the same program. The interactive desktop program was more effective than a non-interactive, but immersive version of the VE. Immersion, therefore, may not always be necessary to improve student understanding.

Global Change World

We introduced this VE earlier. Entering the VE, students find themselves in Seattle. They can recognize landmarks and natural features. Their job is to develop a theory of the causes and effects of global warming and then to reduce it. The VE was built with developing techniques for scientific inquiry firmly in mind.

A typical session [27, 32] goes like this. The student calls up a virtual tool kit, measures air and water temperature with a thermometer, annual rainfall with a rain gauge and amount of CO_2 in the air, in parts per million, using a CO_2 meter. The data from the measurements are shown in a heads up display and recorded by the computer. The student then "dials up" a year in the future and steps through a time portal to that year, where the student repeats the measurements. The process is repeated four or five times. We usually recommend that observations be repeated every 50 years or so. The student then discusses the observations with other students. The group may view plots of the data over time if they wish. They then construct a hypothesis from what they have observed and choose a way to test it. They may manipulate the amount of greenhouse gas emitted by vehicles, the amount emitted by industry, and the amount of green plant matter available to absorb CO_2. A student re-enters the VE, adjusts one or more variables by turning big wheels, and repeats the observations at the same time intervals as before. The process continues until the students have built a viable theory of global warming.

In Global Change World, reification is limited and highly conventional. For example, temperature appears as the height of a column of mercury in a thermometer. Data are displayed as numbers. The fundamental metaphors are likewise predictable: Cars stand for pollution from vehicles, factories for pollution from industry, trees for green plant mass (we noted above how the last of these can create a new misconception). Also, the water level of the sea rises and falls as the polar ice caps shrink and grow. It is possible to flood parts of Seattle, which has quite an impact on the students who know the city well. The most recent version of this VE allows two students, or a student and "expert", to work in the VE at once. The results obtained from students working alone, students working in pairs, and students working with an expert show advantages and disadvantages for each strategy, varying with the kind of information that is learned. These results are reported in detail in [33].

The database available to the user of Global Change World is extensive. Each time a model is run, the program creates predicted values for all variables at one year intervals for the next two thousand years and places them in a look-up table. Any of these data can be accessed when the student chooses a year to visit. This allows students' understanding to be built from information that goes considerably beyond what they would normally be able to access.

Tree World

This VE was built for, and partly by, upper elementary school students (nine- to eleven-year-olds. We have spent considerable time and effort working with students to build their own VEs. See [34]). The students' task is to make a sick tree healthy. They do this by providing it with sunlight - they move a cloud aside and the sun shines - with water - they push a boulder blocking a stream aside so that water can flow to the tree - and with nutrients - they feed grass to a cow that then runs over to the tree and "poops" on the ground beside it. When each operation is completed, the tree becomes progressively healthier. Its branches droop less. Its bark changes from sickly gray to a rich brown. Leaves appear. In one version, once the tree is healthy, creatures that live in trees, that the students built themselves, appear, and the students can interact with them.

Tree World is quite different from the Science Space VEs and Atom World, and to some extent from Global Change World. The differences are appropriate given that it is used by younger children. To begin with, it does not transduce objects that students cannot experience directly. All the virtual objects represent familiar objects. Still, it uses metaphors for natural processes - moving the cloud, moving the boulder and feeding the cow. Incidentally, these metaphors were all chosen by the students, not by us. The metaphors are effective. The students who have worked in Tree World remember them and the processes they stand for. Next, Tree World does not require students to shrink or grow in size, though it does imbue them with "superhuman" powers, like flying up to push a cloud from in front of the sun, and the strength to move a large boulder. Yet far from confusing students, these abilities simply add to the fun.

Tree World allows only minimal experimentation. Students can observe the effect of their actions on the tree (the order does not matter). But the actions cannot be undone and each action has the same amount of effect on the tree's health. This means that students cannot manipulate one variable (sunlight, water, nutrients) while controlling the other two in order to determine which is the most critical.

Virtual Puget Sound

We introduced VPS earlier to illustrate how VEs can be built from extensive databases. Our first study of the effectiveness of this VE for helping students understand water movement caused by tidal currents and the fluctuations in salinity that ensue has provided data about when the VE does and does not help understanding.

Subjects enter VPS with the task of finding the most likely lair of a predatory fish that has recently been discovered in Puget Sound. They are given the fishes' preference for salinity and current speed and are to report the most likely location and depth where it will be found, and at what time in the tidal cycle. At five sites, they can change their depth in the water column and can measure current speed, current direction and salinity using virtual probes. They may also change their time in the tidal cycle and may choose to animate the currents, which appear as vectors whose length shows current speed and which point in the direction the water is moving. They may observe current speed and direction from any height above the water, or from beneath the surface. The data they collect have been produced by the Water Circulation Model, described earlier [29], and "truthed" by oceanographers working from the research vessel "Thompson".

After a pretest, extensive training on how to use the system, training in how to "think aloud" while they are solving the problem, and a briefing on the task, subjects enter VPS. Simultaneous videotapes are made of the subjects and their think-alouds outside the VE and from a video feed from one eye of the helmet. This provides a complete record of what each subject sees and does in VPS. In addition, head and hand positions and attitudes are written to a file every second, and each action the subject performs is written to a file as it occurs.

Not all the data have been analyzed at the time of writing (November, 2000). However, to date we have found that the students did change their conceptions about water movement and salinity in ways that were consistent with what the VE demonstrated. However, for two concepts, some students learned a misconception - in fact, several students who got pretest questions about these concepts right got the corresponding posttest questions wrong! The concepts had to do with how water moves at different depths, and how water flows out of Puget Sound. The first of these requires an understanding of the meaning of arrows that we used to show current vectors. Interviews showed that these were confusing, and could indeed have induced a misconception. The second misconception was that students who saw the same phenomenon made radically different interpretations of it. Water coming into Puget Sound tends to speed up as it passes through narrow straits-- a phenomenon generalizable to any type of fluid flow. However, some students concluded that water moves slower through narrow channels because they are more constricted and therefore less water can get through.

Big Beef Creek

We introduced BBC above. This VE is a work in progress. The VE is a "desktop" three-dimensional visualization, using VRML and Java3D, of the digital elevation model (DEM) of the BBC watershed, an area approximately 15 by 3 kilometers at its widest. Students may assume two avatars, an eagle that lets them fly over the land, and a human that walks on the surface. Up to nine different students (avatars) may be present in the VE at once. Each student uses a different computer, which is connected to the others over a local-area network. Very soon, we expect to enable collaboration using the tool over the web.

Flying and walking are both controlled by a mouse using a custom interface that provides a number of navigation tools. Flying over the land gives the students a plan view of the DEM, though the three-dimensionality is well in evidence thanks to a variety of visual modeling techniques. Walking on the surface gives the student a good sense of what the watershed looks like from that point of view. Position is reported by a constantly updated display of UTM (Universal Transverse Mercator) coordinates, which are standard for this kind of data. In addition, students may use virtual probes to measure values of whatever data are present at the time. We are currently working with a 30-meter DEM and Landsat data, which means that students can measure, say, reflectance in each 30-meter square in a grid covering the watershed. We have datasets with as high as one-meter resolution.

We are currently working with a course of 24 upper class undergraduates and graduate students whose objective is to learn how to take field data and work with them using GIS (Graphical Information Systems) software. We use our BBC tool to orient the students to the watershed and also to help them plan their field work. We are looking at how their mental models of the area are developing and how they use our model to plan and review their activities in the field. To date, our data are too preliminary to report. However, we have built the VE to provide access to a great number of datasets and to provide some interactivity with the environment.

We are also developing an Augmented Reality (AR) version of the BBC VE using software developed by Billinghurst and his colleagues [5]. Students wear goggles to which are attached a small video camera. As they look around the real world, the video stream from the camera goes directly to the goggles, so they can see the world as it really is around them. If the real world contains a table with a map of Big Beef Creek on it, students can place patterned cards on the map, which, like everything else, are picked up by the video camera. If the pattern on the card is recognized by the software, its corresponding three-dimensional object is added to the video stream and appears superimposed in the student's view through the goggles. The student can then pick up the card and thus the virtual object, inspect it from different angles and pass it around to other students' avatars in the world, whether they are physical present or present only over a network. In this way, students might select places at BBC and lift soil strata from the earth, examine these from any point of view, and share them. We believe that this use of AR will prove to be highly empowering and will prove to be a useful tool for bringing about conceptual change.

Section Summary

The various pieces of our conceptual framework are implemented in these VEs in different ways and to varying degrees. Some VEs use reification, others straightforward metaphors and others representations of real objects. Some change students' size, others do not. Some are particularly well-suited to scientific inquiry. Others, more constrained and prescriptive, prevent mistakes and therefore proscribe free-wheeling experimentation. Some provide access to large amounts of data, others do not. In almost all cases, however, the cited research has found evidence for the VEs' effectiveness in helping students develop scientific understanding. However, some of these findings are reported without direct reference to the properties and affordances of the VEs that might account for their success. Our most recent work with VPS and BBC is an attempt to overcome this failing.

CONCLUSION

Our research to date into how VEs can help students understand science (though not necessarily the work of others) has been largely exploratory. Our work on the PRISM project is taking us to a new stage, where we start teasing out when it is and is not advantageous for students to visit VEs to learn science. We have made the argument that VEs are potentially useful for helping students understand scientific theory and to build their own theories. This is because they allow students to enjoy some of the advantages scientists have: Technologies and techniques for extending sensory capability through transduction, reification and metaphor; access to large amounts of information; the ability to engage in the same rigorous and proven inquiry that scientists use. By using scientific methods to extend the experience our students have, VEs should make even counter-intuitive theoretical predictions more acceptable for students.

We have not described the large amount of evidence we have that working in VEs is fun. Using VEs to bring about conceptual change can be an exciting and motivating experience for students. Our VEs often behave in ways that are surprising for students whose explanations of how the world works are based primarily on experience. Students are often surprised that the predictions based on their often counter-intuitive hypotheses are in fact correct. It is the surprise that arises from scientific inquiry that leads us to agree with Dawkins [7] that doing and learning science is far from dull. Science might dispassionately explain what experience can only account for from, say, superstition. One example is Hamlet's statement about the appearance of his father's ghost, which we cited at the beginning of this paper. Yet the tension between theory and experience will always intrigue scientists and students. ee cummings' observation, which we also cited at the beginning, concludes with the remark that, however much scientists and philosophers may poke and prod the earth, in search of its secrets,

? thou answerest
them only with
spring)

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ΣΥΝΟΨΗ

Οι επιστήμες απαιτούν τη σύνδεση μεταξύ θεωρίας και εμπειρίας. Χρησιμοποιούμε τη θεωρία για να ερμηνεύσουμε τις εμπειρίες μας και τις εμπειρίες μας για να κατασκευάσουμε θεωρίες. Το άρθρο επιχειρηματολογεί ότι τα εικονικά περιβάλλοντα βοηθούν το μαθητή στη μάθηση των επιστημών, συνδέοντας τη θεωρία με την εμπειρία με τρεις τρόπους. Παρέχοντας τα μέσα για την αντίληψη και αλληλεπίδραση με φαινόμενα που βρίσκονται πέρα από αισθητηριακές εμπειρίες, παρέχοντας πρόσβαση σε μεγάλο όγκο πληροφορίας, παρέχοντας τη δυνατότητα στο μαθητή να πειραματίζεται με φαινόμενα με τους ίδιους τρόπους, όπως και οι επιστήμονες.

Η έρευνά μας καθοδηγείται από ένα εννοιολογικό πλαίσιο που παρουσιάζεται στο άρθρο, και βασίζεται στα τρία παραπάνω θέματα. Τα αντικείμενα στα εικονικά περιβάλλοντα δρουν ως "μετατροπείς" φαινομένων τα οποία δεν έχουν άμεσα αντιληπτές ιδιότητες. Τα εικονικά περιβάλλοντα δημιουργούνται από βάσεις δεδομένων όσο εκτεταμένες το απαιτεί το εκάστοτε υπό μελέτη αντικείμενο. Τα εικονικά περιβάλλοντα μπορεί να είναι η βάση πολύπλοκων και ισχυρά αλληλεπιδραστικών προσομοιώσεων για την καλλιέργεια εννοιολογικών αλλαγών.

Το άρθρο παρουσιάζει επίσης παραδείγματα υλοποίησης εικονικών περιβαλλόντων για την υποστήριξη της κατανόησης θεμάτων από τις φυσικές επιστήμες που βασίζονται στο προτεινόμενο εννοιολογικό πλαίσιο. Αναφέρονται τα θετικά τους στοιχεία, αλλά και τα λάθη που έχουν γίνει. Συμπερασματικά, τονίζεται η σπουδαιότητα και αναγκαιότητα σχεδίασης και υλοποίησης εμπειρικών ερευνών για τη μελέτη του τρόπου συνεισφοράς στη μάθηση, αυτών των μοναδικών χαρακτηριστικών των εικονικών περιβαλλόντων.

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Finding a Place for Virtual Reality in Special Needs Education: A Review

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ABSTRACT

The illusory realism of interaction with 3-D Virtual Reality environments can be utilised in several unique ways in special needs education. Since the participant experiences movement-contingent sensory changes, this conveys varieties of information that are not available from 2-D displays. In the realm of spatial cognitive training this is especially useful, and children with mobility impairments have been shown to improve spatial function after 3-D exploration. Exploration of schools and public buildings is possible in VR for children with severe mobility limitations. Modelling schools and school environs can potentially help children to overcome spatial anxiety, and can in future assist the investigation of relationships between navigational, visual-spatial and academic subject-related spatial skills. VR needs to be used in ways that promote social inclusion rather than exclusion for children with special educational needs.

Keywords: virtual reality, spatial cognition, school environments, visual-spatial skill, social inclusion

INTRODUCTION

The present paper sets out ways in which Virtual Reality (VR) has been employed in special needs education, to enhance the spatial cognitive mapping skills of children with mobility impairments, who are often found to misinterpret their immediate environment. The first section discusses the particular benefits of VR over other media, and the interactivity issues that need to be addressed to maximise the benefits of using this technology. Joining a new school is particularly daunting for children, and VR might be used to reduce the associated social anxiety. Walking between home and school is currently encouraged for environmental reasons, though it is also an important spatial experience. However, this raises issues of road safety, which VR might help to address. The second section of the paper concerns relationships between large-scale locomotor activities and scholastic achievement. Despite the relative lack of data in this area (and evident inter-individual variation), it seems clear that there are relationships between some measures of spatial skill. Encouraging large-scale navigational skills as one aspect of broader spatial training may have knock-on benefits for class