When Does Immersion in a Virtual Environment Help Students Construct Understanding?

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Abstract: Twenty-six undergraduates were randomly assigned to either an immersive virtual environment or an equivalent "desktop" version, which simulated water movement and salinity in the ocean. Following strategies known to support conceptual change, they sought the best location for a discharge pipe that would disperse treated sewage as effectively as possible in the water. Analysis of overall posttest scores and scores on subtests of knowledge about tides, water movement and salinity, showed that immersed students learned more than non-immersed students, but that this difference was confined to knowledge of water movement. Immersed students also reported being "present" in the environment to a greater degree than non-immersed students, and presence predicted learning. Analysis of videotapes of four of the students showed the emergence of new concepts and the evolution of new principles, and that immersed students took longer to complete the task and said more while doing so. These findings suggest that immersion in a virtual environment helps students construct understanding of dynamic three-dimensional processes, but not of processes that can be represented statically in two dimensions for which "desktop" simulations suffice.

Introduction.

One of the main "selling points" for using virtual environments (VEs) to help students construct understanding has been that they can be "immersive". The student wears a helmet, whose position and attitude are tracked electromagnetically, so that a stereo image can be redrawn in the helmet's eyepieces in real time, to continuously update scene as the wearer's gaze moves around in the VE. The student holds some kind of device with which to interact with the VE – a wand or a game controller – which is also tracked. The student can see a virtual hand that moves as the real hand moves. The illusion that results is that the student is in the VE and can look around just as in the real world. The student can also interact with the VE in quasi-natural ways, by touching objects, picking them up and manipulating them. With the right hardware and a well-designed VE, the interface can become sufficiently transparent to cease to intrude between the student and the environment (Bricken, 1991). The assumption, by educators, is that the directness of the experience the student has of the environment that immersion affords, and the naturalness of the interactions, will improve the student's ability to understand the phenomena that the VE simulates.

Surprisingly, there has been little systematic study of this assumption. That students can learn in VEs is well documented (Dede et al., 1997; Winn et al., 2001). The nature of the experience a student can have in a VE, and why this might lead to better understanding of certain phenomena, have been characterized (Dede, 1995; McLellan, 1996). However, there is little evidence that immersing students in a VE makes it that much easier for them to learn complex curricular material. Since developing and using VEs is still more expensive than preparing programs and activities that work on regular desktop computers, it is important to identify any added value that accrues from visiting a VE, which might justify the extra expense and effort. This study examined this question by comparing what students learned when immersed in a VE with what students learned from interacting with an equivalent desktop program. The VE was an interactive and dynamic visualization of tidal currents and salinity in Puget Sound, Washington, built on a simulation of some of the Sound's physical properties. The VE is called "Virtual Puget Sound", or "VPS".

How Students Learn Science.

Conceptual Change.

Students learn science as their conceptions about how the world works change to become more accurate accounts of natural phenomena (Thorley & Stofflet, 1996; Vosniadou, 1994). Changes in students' conceptions (or the creation of conceptions where none existed before) are fostered by strategies whose effectiveness has been empirically validated (Posner et al., 1982; Windschitl & André, 1998). VPS embodies a number of these. First, students encounter an event that is not predicted by their current conceptions. For example, we have noticed that many students believe tidal currents are greatest at high tide. Letting them observe water movement in VPS at different times in the tidal cycle provides them with evidence that this is not the case. (Water moves fastest between high and low tide.) Second, students must understand why the phenomenon occurred, otherwise they will simply remember it as a fact. Depending on the certainty of the new conception and on how the student explains it, this can be achieved through scaffolding (Linn, 1995), through further experimentation within the learning environment, or through direct teaching. Third, the student must change existing conceptions to accommodate the new one. It must not just be understood; it must be believed and must not contradict other conceptions. For example, observing water movement at high tide will show that it slows down and changes direction before speeding up again. Once thought through, this idea should not conflict with a student's existing conception of "high tide". Fourth, the new conception must be fruitful and used to solve new problems, in the case of VPS, where to run a new sewage discharge pipe. Finally, all of this should take place in an interactive environment that allows the student to test hypotheses, observe and reason about what they observe. Changes in students' conceptions that result from these strategies can be seen in the appearance of new concepts, such as "tidal current", and in new links among concepts to form new principles, such as "tidal current is fastest between high and low tide".

Presence.

Previous research has shown that these strategies can bring about significant conceptual change in students working in virtual environments (Winn & Windschitl, 2002; Winn et al., 2001). This study focused on the particular contribution of immersion to conceptual change. Immersion in a VE can be expected to help certain kinds of conceptions develop. It does this, first, by increasing a student's "presence" while visiting the VE. "Presence" is the sense one has of being "in" the VE rather than in the laboratory or classroom, wearing a helmet and holding a controller. To increase presence, the student must shift attention to the VE and away from the real world (Lin et al., 2002; Witmer & Singer, 1998). This can be accomplished in two ways: Taking away reasons to attend to the real world by removing ambient noise and other distractions; and strengthening reasons to attend to the VE, by making it more engaging. Jackson (2000) used the first strategy. He fed all spoken communication and other sounds to middle school students, collaborating in a VE to control global warming, through headphones in their helmets. Sounds now seemed to come from *inside* the VE rather than from outside, and presence increased. Hoffman et al. (2000) used the second approach. They created a highly-engaging game-like VE for children, who had been severely burned, to use while they were having their wounds cleaned. The children's sense of presence was significantly higher than those who used a Nintendo game for the same purpose. The pain they experienced was dramatically less than that felt by the other children.

There are a number of techniques for directing attention to a VE by making it more engaging. Hedden's (1998) study of why people can spend hours playing a computer game offers some insights. Hedden drew on Lepper and Malone's theory of motivation (Malone, 1980; Malone and Lepper, 1987; Lepper and Chabay, 1985) and proposed that three conditions act to focus attention on games. *Challenge* is greatest when the goal is clear, initial uncertainty is high, and the activities necessary to attain the goal are of intermediate difficulty. *Curiosity* is aroused when students believe that interacting with the game will provide knowledge they need to have, when the game is not too complex to discourage the student, nor too simple to bore her. *Fantasy* arises when the student can imagine a number of possible outcomes to the activity. As the activity progresses, the possibilities are eliminated one by one until just one remains – the solution to the problem.

Virtual Puget Sound was designed to exploit challenge, curiosity and, to some extent, fantasy in order to heighten presence. However, VEs have another property that can assist conceptual change. We call this "transduction" (Winn, 1993; Winn and Windschitl, 2000), whose impact on conceptual change, like that of presence, is expected to increase with immersion.

Transduction.

The bandwidth of the human senses is limited. This means that the view we have of the external world is fragmented and the knowledge we construct of it from direct observation is incomplete. For this reason, scientists do not rely on their senses alone when doing science. Rather, they use instruments to extend the experiences that the senses can provide, both when they describe the world and when they test hypotheses about it. The instruments scientists use act as transducers – they convert the raw data that the world provides into information that *can* be detected by the senses, in visual and acoustic displays, for example. A VE also acts as a transducer (Winn and Windschitl, 2000). It can make visible (and audible and touchable) data from a database that sits beneath a simulation of some phenomenon. Thus, in a VE, students can see and interact with subatomic particles (Byrne, 1996), the ocean floor (Windshitl and Winn, 2000), or complex organic molecules and electrostatic fields (Dede et al., 1997).

Transduction is possible because VEs are constructed digitally. Objects in a VE are created from a database, regardless of whether they represent objects within or beyond direct sensory experience. Thus, models of real and virtual objects have equal phenomenological status in a VE. However, the presence that arises from within a VE increases the illusion that virtual objects are as real as real objects. The distinction between learning directly from the world and learning from symbolic representations of it largely disappears. This means that students can learn concepts and principles directly, without having to master a separate and often difficult symbol system first (Dede, 1995; Winn, 1993). A difficulty arises, however, because phenomena beyond direct sensory experience can only be represented in a VE as metaphors (Osberg, 1998; Winn, Hoffman & Osberg, 1999). Ill-chosen metaphors can create new misconceptions, as in the case of the student who inferred that water slows down when it enters a narrow channel (Winn et al., 2001). The metaphor for water movement was animated arrows, whose length showed current speed. The student reasoned that faster water, shown by longer arrows, appeared to "clog up" the narrow passage. When the highway is clogged with traffic, you slow down.

The potential for VEs to help students construct understanding of the world comes from a VE's ability to embody strategies known to support conceptual change, and from its unique ability to immerse a student in an interactive environment. Our hypothesis was that immersion heightens presence and therefore the students' engagement in the VE. This in turn makes it likely that metaphors used to represent phenomena beyond normal sense experience will be convincing and effective carriers of the information that leads to the acquisition of new concepts and the construction of new principles by linking concepts together. To test this hypothesis, we conducted a study of how a VE, designed to be challenging and to maximize curiosity, helped students understand basic principles of physical oceanography. In the study, we compared conceptual change in two groups of students. One group was immersed in the VE. The other group worked with the same VE on a desktop computer.

Method

Materials: Virtual Puget Sound.

Virtual Puget Sound (VPS) is a computer simulation of tidal currents and salinity in Puget Sound, Washington. It describes water speed, water direction and salinity at half-hour intervals during one tidal cycle (roughly 24 hours), at twelve different depths and at points on a 600 by 900 meter grid over the entire Sound. Water speed, direction and salinity are measured by virtual instruments that provide digital readouts. Water movement is shown by how particles move throughout the Sound. The student may release particles, from single or multiple sources, at different places and at different depths. Students can start and stop time. When running, time is speeded up so that one 24-hour tidal cycle is compressed into around five seconds. Students can set the point in the tidal cycle directly by moving a vertical line to points on a tide graph. Students navigate through VPS, above and below water, and interact with it using a Space Orb® computer game controller. They access and use the tools by pressing buttons.

For this study, we built two versions of VPS. One version used VR technology to immerse the student in the VE. The other version displayed the VE on a desktop computer screen. All other features of the two versions were identical, including interaction through the same game controller.

Students.

Students were undergraduates enrolled in computer science and information science courses. They were randomly assigned to the immersed or the desktop treatment. Usable data were obtained for two groups of 13 students.

Tasks and Procedures.

Students worked individually in VPS to come up with a recommendation to King County about where to locate the end of a new discharge pipe for treated sewage, so that it would be carried out of the Sound as quickly and completely as possible. They started by completing a questionnaire that asked about their familiarity with the region and pre-tested them on the content. The pretest questions were multiple choice and short answer, seeking both knowledge and explanations of the relevant oceanographic phenomena. They tested knowledge of three topics, the daily tidal cycle, water movement and salinity, with five questions devoted to each topic, each question consisting of a multiple choice part and a short answer explanation for the choice. Students visited VPS on three separate occasions – for training, and twice to test predictions about water movement and salinity and to release particles to test their predictions – before making their recommendation to the County. Before the second and third visits, they drew on maps of the Sound and provided written and spoken explanations to show where they thought the water would carry the particles they were about to release, how salinity would change, and so on. Their activity was videotaped. They were encouraged to talk out loud while working in the VE, and were occasionally questioned during their work, although they were not formally trained in think-aloud techniques. On completing the tasks, they were interviewed, took an objective and short-answer posttest on the content, questions again covering the same three sub-topics. They also rated their presence on a five-point scale, the standard way of assessing presence (Hoffman et al., 1995). The time required for the students to complete the tasks in VPS averaged to just under an hour. The total time they spent, including training, tests and interviews, was approximately two hours.

Data analysis.

One kind of evidence for conceptual change can be found through statistical analysis of quantitative measures of what students know before and after visiting the VE. Pre- and posttest items were scored as follows: one point was given for a correct answer on the objective part of the item, and between 0 and 2 points were awarded for the written explanation. A score for the suitability of the recommended location for the pipe was given based on the choice of site and the reason for the choice. Posttest scores for the two groups were compared using analysis of covariance, with pretest scores as the covariate. (The pretest scores between the two groups were noticeably different, though not significantly so.) These analyses were repeated on the three subsets of performance scores: for water movement, for salinity, and for knowledge of the tidal cycle. Post-experience presence ratings were also compared, using a t-test. Regression analysis was used to determine whether presence predicted posttest scores.

As we mentioned earlier, another kind of evidence for conceptual change is the appearance in student discourse of new concepts (e.g. "tidal current") and principles (e.g. "tidal current is fastest between high and low tide"). We transcribed the tapes of two immersed and two desktop students, one of whom in each pair was male and one female. Because we were looking for evidence of conceptual change, we chose students whose posttest scores were at least 30% higher than their pretest scores. We examined the transcripts for the development of concepts and principles during two activities. The first was release of particles from five sources arranged in a line across a narrow part of Puget Sound. The second was release of particles in one location at five different depths.

Results.

Quantitative evidence for conceptual change.

Immersed students rated their presence higher than non-immersed students ($t_{(25)}=2.64$, $p<.05$). Analysis of covariance, with the overall pretest score and scores on the three sub-pretests as covariates, showed that immersed students scored better than non-immersed students on the overall posttest ($F_{(1,23)}=7.45$, $p<.05$) and on the sub-score for water movement ($F_{(1,23)}=8.90$, $p<.01$). Scores on the separate salinity and tidal cycle tests were not significantly different. Immersed students were also better a picking a good site for the sewage outfall, though not significantly so ($t_{(25)}=1.81$, $p<.10$). Linear regression analysis showed that rated presence predicted posttest scores, (standardized regression coefficient β=.44, t=2.87, p<.05).

Evidence from analysis of videotapes.

Examination of the videotape transcriptions showed many examples of conceptual development. The first task required the students to release particles simultaneously from five sources in a line at the surface across a narrow part of the Sound. The key principles students were intended to acquire connected water depth, the speed and direction of the current over the tidal cycle, and the location of the particle release point. Water on the East side is shallow and particles tend to move more slowly in an East-West oscillation. Water on the West side is deeper and the water moves in an overall northerly direction. All four students correctly learned the relationship of water depth and current speed, and the effect of location on these factors. For example:

> *Immersed male student.* " … looks like the ones moving the fastest are the ones close the shore on the West … and they're pretty slowly moving to the North." [Referring now to particles close to the East shore], "Yeah, looks like they're pretty stagnant, they didn't move very far, and looks like there's really shallow water right there … Yeah, the ones on the East side approach the shore, the ones more West move basically to North."
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> *Desktop female student, (non-native English speaker).* "One that [points to screen to indicate particles on East of the channel] is beside the shallower … water stays there, but the one stays on the deeper the water moves … faster, bigger, lighter and they go up North."
>
> *Desktop male student.* "The four yellow dots [particles] on the left [West] are moving in the same sort of movement, up and down, up and down. But when it's close to shore, you know, the water seems to be moving much toward East a little bit … and of course they're not moving as much, I guess."

The second activity had students release particles at five different depths. The location was a point where three channels converge and where water moves generally Northwest at the surface, South at the bottom, and somewhat Northeast in the middle. Again, the students learned the principles:

> *Immersed male.* "Okay, the deeper layers are moving South. And the, uh, surface layers are more or less … well, they're moving slightly Northwest. … OK, so there's a split between the below surface layers are moving North and West and Northeast and then to the South … "
>
> *Desktop female.* "The deepest one moves as big and as fast as the one at the top …; but they go down South, whereas the top one goes up North."
>
> *Immersed female.* "The ones on the surface are going, uh, more North … The ones in the middle are actually going up … North, but Northeast. And then, some are going South … the two bottom things I think … are going South."

From these examples, as well as from examination of activity during other activities, there were no obvious differences between immersed and non-immersed students in the way concepts and principles were acquired. However, four other observations are noteworthy. First, the two immersed students looked around the VE much more than the non-immersed students. Second, the non-immersed students frequently referred directly to the computer screen by pointing as they explained what they were seeing and inferring. (Of course, the immersed students could not do this.) Third, immersed students took longer to complete the two activities. Finally, the immersed students uttered more words for each activity than the non-immersed students.

Discussion.

The finding that immersion improved understanding of water movement but not of tides or salinity is best explained by considering the difference between the immersed and desktop conditions, and by examining the differences in what students needed to do to learn about water movement, salinity and tides. Since both groups used the same controller, the only difference between the experiences that the two groups had was that immersed students could look around them simply by moving their heads, while students using the desktop version had to change the direction in which they were looking by twisting a ball on the controller. For the immersed students, looking around was as natural as it is in the real world. For the desktop students, it required an overt, unnatural manipulation. Indeed, our examination of the tapes showed that the immersed students did look around a lot more than the non-immersed students, and to get a good sense of how the water moved, in three dimensions and in different locations, it was necessary to look around. This was not the case for changes in salinity, which were only viewable as digital readouts in a virtual instrument. Nor was it the case for tides, where information was most readily available from a graph of the tidal cycle. We can therefore conclude that immersion allows students to visually examine their surroundings naturally in a VE, and that this enables them to better view the information they need to develop conceptions of water movement, which is a dynamic, three-dimensional, somewhat unpredictable, phenomenon. Supporting evidence for this conclusion is found in the findings that immersion increased presence and that presence predicted learning. This interpretation is also supported from a study of learning three-dimensional layouts in VEs. Arthur, Hancock and Telke (1996) had subjects view virtual landscapes containing three-dimensional geometric solids, either from a fixed position or while walking around the landscapes. Subjects who were free to move about, and therefore to change their point of view, showed significantly better recall of the landscapes.

Conceptual change, seen when students make new connections among concepts, did not appear to occur differently in the two immersed and two non-immersed students whose tapes we examined. This is not surprising, given the small sample and that the four students were chosen because their test scores showed that their conceptions had changed considerably. However, the observations made of these four permit other conclusions. Immersed students looked around more than the non-immersed ones, taking advantage of the fact that this is easier to do when you are immersed. Yet requiring more time to complete the task and to explain what they were doing suggests that the immersive interface is less conducive to communication than sitting at a computer screen, to which you can point as you make observations and explanations. This suggests that, for effective collaboration, all participants should be immersed in the VE (Jackson, 2000).

Together, these findings lead to the recommendation that the extra cost of immersion only pays off when the content to learn is complex, three-dimensional and dynamic, and when the student does not need to communicate with "the outside" while working.

This study did not establish that the students experienced optimal challenge, were motivated by curiosity, or exercised fantasy, although this version of VPS was designed with these in mind. A next step in this research is to determine more clearly the role of these factors, known to affect engagement in computer games, in inducing presence and supporting conceptual change in VEs. In addition, we need to study conceptual change while working in VEs in other types of student. Our students from computer science and information science were likely more savvy about simulations and experimental interfaces than others. Our current work will permit us to take VPS, which we are modifying to run on laptops, and extensions of it into public schools. We are looking forward to studying how immersion in VEs can support conceptual change in younger students and how VEs, immersive or not, can support standard science curricula.

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