Deep Learning in Virtual Reality:
How to Teach Children That the Earth is Round

Stellan Ohlsson (stellan@uic.edu)
University of Illinois at Chicago
Department of Psychology (MC 285)
1007 West Harrison Street
Chicago, IL 60607-7137

Thomas G. Moher (moher@uic.edu)
Andrew Johnson (ajohnson@uic.edu)
University of Illinois at Chicago
Department of Electrical Engineering and Computer Science (MC 154)
851 South Morgan Street
Chicago, IL 60607-7053

Abstract

To understand deep cognitive change, we have to understand how learners can go beyond their own prior knowledge. We propose a *displacement scenario* in which a learner acquires a target idea in a different context and then transfers that idea into a target context. We used virtual reality technology to implement a displacement scenario for teaching 2nd grade children that the Earth is round. The rather large pre- to posttest improvement was stable over four months.

The Paradox of Deep Learning

Knowledge systems are organized along a center-periphery axis. One or more *central ideas* dominate more peripheral ones. The center-periphery structure is particularly obvious in scientific theories (Lakatos, 1980), but it also plays an important role in cognitive development (Chi, 1992; Vosniadou, 1994), social cognition (Eagly & Chaiken, in press; Rokeach, 1970) and elsewhere.

Changing the peripheral parts of a knowledge system by learning new facts or skills is easy enough, but revising its core concepts -- *deep learning* -- is a different matter (Ohlsson, 1995). Both direct experiences and communications are interpreted in terms of, and with the help of, prior ideas and hence tend to be understood as consistent with them. The result is that people assimilate information that is anomalous or inconsistent with current ideas or beliefs either by misunderstanding the former or by revising peripheral parts of the relevant knowledge system (Chinn & Brewer, 1993; Darden, 1992; Kuhn, Amsel & O'Loughlin, 1988; Strike & Posner, 1992). Consequently, neither direct experience nor communications have much power to change central ideas. Fodor (1976, Chap. 2) has argued that this is necessarily so: A less powerful representational system cannot, in principle, replace itself with a more powerful one.

This conclusion leads to a paradox (Bereiter, 1985). It implies that central ideas never change, but of course they do. Scientists sometimes revise fundamental theoretical principles and non-scientists undergo radical changes in world view, particularly during childhood. Developmental psychologists have documented deep changes in children's understanding of a variety of domains (see, e.g., Hirschfeld & Gelman, 1994). Gopnic and Meltzoff (1997) argue that such developmental changes share many features with theory change in science.

How is deep cognitive change possible? How does the mind circumvent the learning paradox? One plausible hypothesis is that ideas that are new in one domain are brought into that domain from some other domain. According to this *cross-domain transfer hypothesis*, to acquire a new central idea in a target domain X, the learner must first acquire that idea in some source domain Y in which its acquisition is not hindered by prior knowledge, and then transfer the new idea to X and build a new understanding of X around it. The new understanding will gradually replace the old. This hypothetical three-step process might circumvent the distorting influence of the learner's prior ideas about X.

This hypothesis predicts that we can facilitate the acquisition of a deep idea if we displace the learner's attention from the target domain to some other domain, teach him or her the target idea in that domain, and then prompt him or her to transfer it into the target domain. We implemented this *displacement scenario* in a virtual reality environment for teaching children that the Earth is round. Empirical evaluation in a public school resulted in strong and lasting improvement in the children's understanding of the shape of the Earth and related facts.

Mental Models of the Earth

All direct experience supports the idea that the ground is a flat surface extending in all directions; hills and valleys are only local perturbations. The sky is parallel to the ground, the ground is always *down* and the sky is always *up*.

These ideas partition the universe into two unequal regions, above and below the Earth. They strongly imply that traveling in a straight line will bring the traveler further and further away from his or her starting point, until he or she reaches a boundary where the Earth stops. Furthermore, *down* and *up* do not vary with the observer's location; an arrow pointing upwards in one location is parallel to an arrow pointing upwards in any other location. Also, objects at a distance are hard to see either because they are occluded by another object or because the observer lacks visual acuity. Finally, the location of the sun and the moon when we cannot see them is problematic. Many children in Western (Nussbaum, 1985; Vosniadou & Brewer, 1992) as well as non-Western (Vosniadou, 1994) societies develop some version of this mental model.

The idea that the Earth is spherical has contrasting implications: It suggests that the surrounding space is uniform and it implies that a traveler who keeps going in a straight line will eventually return to his or her starting point. Furthermore, *down* and *up* varies with the observer's location; *up* in New York is not parallel to *up* in Hong Kong. Also, distant objects are invisible because they are occluded by the surface curvature. Finally, the sun and the moon are sometimes invisible because they are occluded by the planet itself.

The shift from a flat Earth to a round Earth view is an instance of deep learning. The two concepts, clearly stated, contradict each other and they influence many other aspects of one's understanding of Earth-related facts and events. Empirical research has shown that this shift takes considerable time, at least two years (Vosniadou & Brewer, 1992, Table 4) and possibly as long as six years (Nussbaum, 1985, Fig. 9.16) when it occurs spontaneously, and it requires one or more intermediate mental models. The question is whether this process can be speeded up with the displacement strategy.

A Virtual Asteroid

Our approach to facilitating the shift from a flat to a round Earth is to teach the idea of a spherical planet in an unfamiliar context, unhindered by prior ideas, and then prompt the learner to apply this idea to his or her knowledge about the Earth. We accomplished the first step in this two-step procedure by using two linked virtual reality (VR) environments. The *Asteroid World* simulates the experience of walking on the surface of an asteroid with approximately 300 yards diameter. The virtual asteroid is roughly spherical in shape and exhibits a desert-like landscape with a handful of geographical features (a bulge, a canyon, etc.), large rocks scattered here and there and fantasy structures that resemble trees made out of crystal, plus a shuttle-like space ship. The sky is black but features stars and a large, moon-like object. The Asteroid World was presented via a so-called *ImmersaDesk*, a VR projection device developed at the Electronic Visualization Laboratory at UIC. The ImmersaDesk is roughly 6 feet by 4 feet. The device supports full immersive VR with stereo vision, head tracking, hand tracking and audio; see Czernuszenko, Pape, Sandin, DeFanti, Dawe and Brown (1997) for a technical description.

When the Asteroid World user presses the forward-move button on the control stick, he or she has the visual perceptions that would be associated with a physical walk on a real asteroid with the same properties as the virtual one. When the diameter of the world is 300 yards, one can experience its sphericality directly. The horizon is very close, rocks and other large objects appear over the horizon very quickly, the stars in the sky are streaming past at a perceptible pace, objects are difficult to find because they are hidden by the curvature even when close by and circumnavigation is accomplished in a couple of minutes.

Our second environment, called the *Mission Control*, presents a satellite view of the virtual asteroid, projected in stereo on a computer monitor. When the user wears stereo glasses, he or she sees the virtual asteroid as a three-dimensional body floating in space against the background of stars. The various geographical features and the space ship are clearly visible. In addition, the Mission Control user sees the user of the Asteroid World as an avatar, a small space-suited figure. That is, the Asteroid World user and the Mission Control user access the same virtual reality at the same time but from different points of view. In particular, Mission Control can observe the movements of the astronaut on the virtual asteroid in real time. To remain in visual contact, Mission Control can rotate the asteroid (but not change his or her distance from it) by pressing a button on a control stick.

The Asteroid and Mission Control environments are described in more detail in Johnson, Moher, Ohlsson and Gillingham (1999). By alternating between them, the learner can experience or perceive the uniformity of the surrounding space, circumnavigation, the relativity of up and down, and occlusion by surface curvature. Furthermore, these experiences occur in a context in which the learner has no prior, conflicting ideas about the shape of the world. The second step in our learning scenario -- to transfer and apply this idea to the everyday experience of the Earth -- is described below.

Empirical Study

Method

Materials The equipment needed to project the two virtual environments was set up in a large room in a public school in a Chicago suburb. The user of one environment could not see the other environment or its user, but the two users were close enough so that they could talk to each other.

In addition, our instructional procedure required two physical models. One was a foam rubber model of the virtual asteroid, approximately eight inches in diameter, painted and equipped with a model space ship, rocks and other features to make it recognizable as a model of the virtual asteroid as seen in the Mission Control environment. The second physical model was a standard Earth globe purchased in a book store.

Knowledge test To assess children's understanding of the shape of the Earth, we developed a structured interview derived from those used by previous researchers (Nussbaum, 1985; Vosniadou & Brewer, 1992). The interviewer (a project team member) asked 18 questions about the shape of the Earth, the content of the region below the Earth, circumnavigation, the relativity of up and down and occlusion by curvature. The children's answers were classified at testing time by the interviewer, using a set of coding categories derived from a pilot study (Johnson, Moher, Ohlsson & Gillingham, 1999). The knowledge test interview took 10-20 minutes. The same test was used as pretest, posttest and delayed posttest.

Subjects All fifty second-grade children in the participating class rooms were pretested. The 28 children who answered 10 or fewer pretest questions correctly were included in the *treatment group*. Due to the small number of such students, we preferred to include all of them in a pretest-posttest design over dividing them into two groups in a treatment-control design. The 22 children who answered 11-13 questions correctly will be referred to as the *comparison group*, although it is not a control group in the statistical sense due to the non-random group assignments.

Procedure For the children in the treatment group, the procedure consisted of pretest, VR experience, bridging activity, posttest and delayed posttest. For the children in the comparison group, the procedure consisted of pretest and posttest.

(a) VR experience. The children were paired into teams of two. During the *familiarization phase*, the two experimenters who acted as guides helped the children put on the stereo glasses and guided them around their respective environments for five minutes. The two children then switched places and the familiarization process was repeated for another five minutes. During familiarization, the guides pointed out visual features related to sphericality (nearness of horizon, objects coming up over the horizon, the avatar seeming to be up side down, circumnavigation, etc.).

During the *game phase*, the children were told that they were stranded on the asteroid for lack of fuel and their task was to find extra fuel cells scattered over the asteroid so that their space ship could return to Earth. The child on the asteroid collected the fuel cells, but the child in Mission Control assisted by locating fuel cells (the latter were clearly visible in the Mission Control view) and by giving directions to the other child. The children played this game for ten minutes, switched places and continued for an additional then minutes. Each child thus had a total of 30 minutes (5+5+10+10) of interaction with the two VR environments.

(b) Bridging dialogue. Immediately after the VR experience, the two children were escorted to two different rooms for the *bridging dialogue*, a structured conversation with a member of the project team. The purpose of this dialogue was to prompt reflection on the VR experience and to help the child transfer the spherical planet idea to his or her mental model of the Earth. In each phase of the dialogue, the experimenter reminded the child of his or her VR experience with the help of the physical model of the asteroid, re-enacting some facet of that experience (e.g., circumnavigation) with toy figures. The experimenter then shifted the child's attention to the globe of the Earth and told him or her that what was the case on the asteroid is also the case on the Earth, enacting the relevant facet with toy figures vis-à-vis the Earth globe. The conversation then switched back to the asteroid model to cover another facet of sphericality, which was also illustrated with the Earth globe; and so on. The bridging dialogue took approximately 15 minutes.

(c) Posttest. The subjects were posttested 24 hours after the learning experience.

(d) Delayed posttest. The delayed posttest was administered four months after the learning experience.

Results

Figure 1 shows the outcome. The performance of the treatment group increased from a mean of 7.3 correct answers on the pretest to a mean of 12.9 correct answers on the posttest. We tested the posttest mean with a single-sample t-test, using the pretest mean as the comparison value. The difference is statistically significant ($t = 13.68$, $p < .000$). Hence, the treatment group improved from pretest to posttest. The magnitude of the improvement is 12.9 -7.3 = 5.6 scale units, which is 1.9 times the standard deviation on the pretest. The mean number of correct answers on the delayed posttest was 11.4. Almost the entire pre- to posttest improvement was retained four months later.

Because the posttest questions were identical to the pretest questions, there is a possibility that the improvement in the children's understanding of the Earth was caused by the test itself. We can use the comparison group to measure the effect of the test. The members of the comparison group were pre- and posttested but did not undergo the VR experience. The mean number of correct answers in this group was 12.2 on the pretest and 14.0 on the posttest. A single-sample t-test of the posttest mean, using the pretest mean as comparison value, showed that the pre- to posttest difference is statistically significant ($t = 4.6$, $p < .000$).

Hence, taking the test prompted some learning, even in the absence of the VR experience. The magnitude of the effect is 14.0 - 12.2 = 1.8, which is .6 times the standard deviation on the pretest. This improvement is considerably smaller than the improvement in the treatment group. Due to the non-random assignment of subjects to groups, the evidence provided by this analysis is admittedly weaker evidence than that provided by a proper control group.

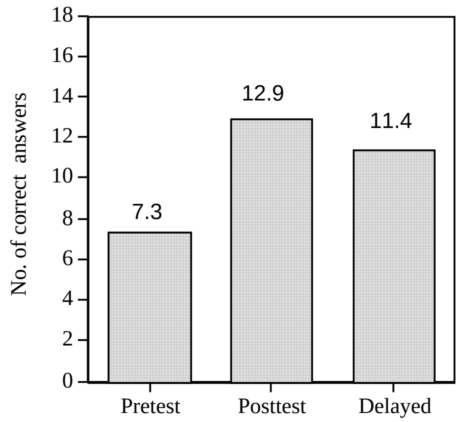

Figure 1. The mean number of correct answers on three test occasions.

A t-test for independent samples shows that the difference between the treatment and comparison groups on the pretest was statistically significant ($t = 10.71$, $p < .000$). There was no significant difference between the two groups on the posttest ($t = 1.90$, $p > .06$).

Discussion

The children in the treatment group almost doubled their understanding of the shape of the Earth, as measured by our knowledge test. The treatment group initially performed considerably below the comparison group, but performed as well as the latter on the posttest. That is, our learning scenario allowed those children who had not spontaneously acquired an understanding of the shape of the Earth to catch up with those who had. Unlike the spontaneous acquisition process, which occurs over several years (Nussbaum, 1985; Vosniadou & Brewer, 1992), the displacement scenario enabled children to acquire the target idea in one day. They retained it four months later.

Why was the displacement scenario successful? An explanation for these results must deal with the paradox of deep learning: Central ideas are seldom transformed by novel input; they are too protected by the surrounding belt of auxiliary ideas and beliefs. So how does deep learning ever come about? The cross-domain transfer hypothesis claims that central ideas are not transformed but replaced by ideas transferred from other contexts, domains or situations (Chi, 1992). In the present study, both our virtual asteroid and the Earth can be said to belong to the domain of elementary astronomy, but the crucial point for learning is that our subjects had no prior knowledge about the shape of the virtual asteroid but they did about the shape of the Earth.

This model of deep learning differs significantly from other models, e.g., attempts to view deep learning in children as analogous to scientific theory change (Gopnik & Meltzoff, 1997; Hewson & Hewson, 1984; Posner et. al, 1982). One difficulty with this theory theory, as it has come to be known, is that human beings are not conspicuously good at evaluating evidence, presumably the central process in theory change. The theory theory describes cognitive change in logical rather than naturalistic terms (Ohlsson, 2000). It does not explain our results, because we did not present our subjects with evidence of any kind: We familiarized them with a previously unfamiliar environment and then asserted that what was true in that environment is also true about the Earth. The cross-domain transfer hypothesis does better because, unlike the theory theory, it does not claim that dissatisfaction with prior ideas is a prerequisite for learning. Prior ideas are not necessarily falsified or rejected; instead, they fall into disuse when another, more useful idea becomes available.

Unlike the knowledge-in-fragments theory of DiSessa (1988, 1993) and Smith, DiSessa and Roschelle (1995), the present theory does not represent deep learning as a process of clarifying, organizing and systematizing so-called phenomenological primitives. Instead, it claims that a central idea that has been transferred from a different context can serve as a starting point for a new understanding of the target context. One difficulty with the knowledge-in-fragments view is that it is unclear how systematizing and organizing can engender a new idea that directly contradicts one of the ideas available at the outset. For example, it seems implausible that experience of the virtual asteroid would prompt our subjects to organize their no doubt fragmented knowledge of the Earth in such a way that they suddenly realized that it must be spherical.

Although our results are more consistent with the cross-domain transfer hypothesis than with these alternative hypotheses, the present study is limited in several respects. The number of children was small, we had no proper control group and the results do not allow us to separate the effects of the virtual reality experience from the effects of the bridging dialogue. We are currently completing a follow-up study that addresses these limitations.

In addition to its theoretical interest, the cross-domain transfer hypothesis might have practical importance. It is a commonplace in educational discourse that good instruction should connect to the students' prior knowledge and experience. However, this pedagogical tactic is unlikely to be productive in those situations in which the target subject matter conflicts with the students' prior knowledge (Ohlsson, 1999; Strike & Posner, 1992). The alternative is to teach the new idea in a different context and help the student transfer it to the target domain. Because many scientific ideas conflict with ideas derived from experience (e.g., inertia), the displacement scenario has the potential to be a useful tool in science education.

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