Spatial and Temporal Embedding for Science Inquiry: An Empirical Study of Student Learning

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Abstract: In consecutive years, a fifth grade teacher of a self-contained classroom enacted five-week Earth sciences units that included learning activities focusing on the interpretation of seismograms and the location of earthquake epicenters. In one class, the unit utilized an *embedded* design that situated learners within the spatial and temporal extent of the phenomenon during the epicenter determination activities. In the other class, while the activity set remained the same, the embedding features were removed. Students in the embedded condition demonstrated greater learning gains than their non-embedded counterparts in pre-post assessments of student skill, declarative knowledge, and conceptual understandings, even among topics unrelated to the determination of epicenters. Post-activity student interviews evidenced strong preference for the immersive, asynchronous, and temporal staging components of the embedded condition.

Introduction

In designing classroom-based learning activities to support science inquiry, one of the most significant challenges is the choice of strategies through which learners might engage with the phenomenon under study. While technologies as old as the printed page have expanded the modalities of engagement and broadened the range of accessible phenomena, they sometimes do so at the cost of some distancing of the learner from the phenomena themselves. As a consequence, learners sometimes lose the opportunity to experience some of the challenges—and excitement—inherent in conducting investigations.

In this paper we report the results of a quasi-experimental empirical study of learner outcomes associated with an activity structure that seeks to shape learner inquiry experiences by *embedding* them within the spatial and temporal extents of the scientific phenomenon of a series of earthquakes. Spatial embedding is implemented by introducing the conceit that the classroom itself is a (scaled) area of seismological activity situated on a tectonic plate boundary. Over the course of about a month, learners experience a sequence of simulated earthquakes—"RoomQuakes"—at unpredicted times, embedding them within the (scaled) temporal course of the phenomena. Students are challenged to locate the plate boundary bisecting the classroom by reading simulated seismograms from seismometers situated around the classroom and using trilateration to combine those results in a way that permit them to determine the epicenters of the seismological events.

In previous reports, we have described the "embedded phenomena" framework (Moher, 2006) and described learner outcomes for a similar RoomQuake unit relative to a no-treatment control (Moher, 2008). Here we extend that work by contrasting the learner outcomes of a fifth grade classroom engaged in an Earth sciences unit on earthquakes incorporating the embedding strategies described above with those of a second class, taught by the same teacher, that received the same instruction and enacts the same set of activities within a *non-embedded* framework. In this second condition, the seismological inquiry is centered on the determination of a fault line in southern California based on the sequential massed analysis of an historical series of earthquakes, using maps rather than the classroom space as the locus of trilateration. Learners were assessed before and after the unit across multiple outcome spaces, including skill in the interpretation of seismograms the use of trilateration, and understandings of the temporal, spatial, and intensity distributions of earthquakes. We also assessed structural and causal content domain understandings associated with the surrounding instructional unit, such as the structure of the Earth and the causes of earthquakes, that were not directly associated with the fault-line determination activities. After the unit, we probed the impact of embedding by posing hypothetical choices between the treatment learners had received and the alternative treatment. In the following we report on these outcomes and discuss their implications for our understandings of how specific elements of the "embedding" might impact learning.

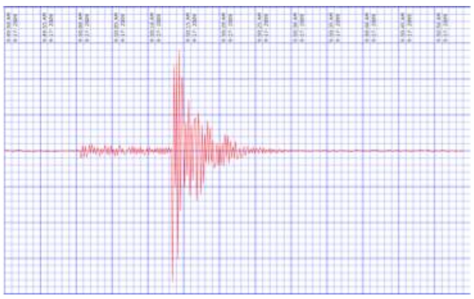
Figure 1. Simulated strip-chart seismogram used in RoomQuake.

RoomQuake

In the embedded version of RoomQuake, students adopt the pretense that their classroom is an active seismic field, and that a series of earthquakes is expected over the course of several weeks within that field. Computers running conventional browsers, served from our laboratory, act as simulated seismographs (Figure 1) that depict continuous strip-chart recordings (seismograms) of local vibration, where locality is conditioned upon their specific placement of the computers within the classroom. Most of the time, the seismograms reflect a low level of background vibration. At (apparently) unpredictable times, rumbling speakers at each seismograph signal the onset of an earthquake. Upon this signal (or as soon thereafter as classroom instruction permits), students move to the seismographic stations to read the waveforms.

Reading the seismogram recorded at a single location provides two critical pieces of information: the magnitude of the event, and the distance (but not direction) of the event from the recording station. Determining the epicenter of an earthquake requires readings from multiple sites, which may be combined together through the process of trilateration to obtain a location solution. In the embedded version of RoomQuake, we use calibrated dry-lines anchored at the seismographs to sweep out arcs of potential epicenter loci; the solution is obtained when the students at the end of those lines converge at a common point. Once the location and magnitude have been determined, the teacher hangs a color-coded (representing magnitude) Styrofoam ball from the ceiling at the epicenter point, providing an historical record of the event series, and students update poster-based representations of the temporal and intensity distributions of the events (Figure 2).

Figure 2. Photo of classroom hosting embedded version of RoomQuake. Styrofoam balls on the ceiling mark event epicenters, color-coded by magnitude. Wall charts are used to track timing and magnitude of event series.

Embedding as an Activity Design Strategy

Spatial Embedding

A central component of our framework is the conceit that the phenomenon under investigation is unfolding within the confines of the classroom itself. This is not an obvious choice, nor necessarily the correct one. When studying seismology, for example, many learning researchers would argue that authenticity demands that the discourse be situated in a scientifically accurate geographic framing; we should be talking about earthquakes around the Ring of Fire, for example. We conjecture, however, that by situating the phenomena “in here” rather than “out there” we might increase learners’ emotional interest in the phenomena, and leverage incidental associations between the simulated and real worlds (e.g., “the epicenter was right over my desk”). Moreover, we hope that by situating the imaginary phenomena within the classroom space students can build on their accumulated knowledge of the physical, social, and cultural features of the environment as they undertake a new type of activity.

Another feature of our approach is the decision to maximize the nominal spatial extent of imagined phenomena by scaling them (up or down) to fill the physical space of the room. From a perceptual perspective, we hope to increase the salience of the phenomena for learners (Collins et al., 1991; Yantis & Egeth, 1999). On a more practical level, we also believe that this strategy can reduce congestion in the classroom by allowing students to use the entire floor space as they conduct their investigations.

In embedded phenomena, access to the representation of the state of phenomena is physically distributed throughout the space of the classroom. We believe that this offers three important benefits. First, it creates multiple natural contexts for students to engage in discourse with peers and teachers (Vygotsky, 1978) concerning the phenomenon. Second, it reinforces the important science concept that understanding the state of a phenomenon might not be possible from a single observation, but may require multiple probes from different vantage points that require aggregation and coordination to come to full understanding. Third, we expect that by requiring physical movement from one part of the room to another in order to obtain complementary data we might reinforce memory by associating it with a physical action (Wisneski, et al., 1998).

Our strongest motivation, however, draws from a desire to physically immerse learners within the experience (Dede et al., 1997); in our framework, not only are the phenomena embedded in the space, indeed the learners themselves are embedded within the phenomena. The importance of embodiment has strong advocates both in psychology (Johnson, 1987; Clancey, 1997; Clark, 1997; Glenberg, 1997, 1999; Winn, 2003) and human-computer interaction (Dourish, 2001). Embodiment approaches argue that “thought grows from action and that activity is the engine of change” (Thelen, 1995). In this perspective, cognition arises specifically through bodily interactions with the world. Learning that pairs action and knowledge, or engagement in goal-directed actions, particularly within social contexts (Lindblom & Ziemke, 2007), is viewed as necessary for higher cognitive capacities of thought and understanding to develop.

Temporal Embedding

The embedded phenomena framework engages the issue of time along two important dimensions: duration and persistence. The long time course of these deployments offers three important benefits. First, it opens the door to the study of phenomena that unfold slowly, requiring investigative processes unlike those used in most classroom science work. A second potential benefit lies in the value of time for students to become meaningfully involved in the enterprise of scientific investigation: different learners engage in activities at different paces. Our prior classroom experience (Moher, 2008) led us to expect that while highly motivated, achievement-oriented students would readily become engaged in our activities, other students would need time to move, in Lave and Wenger's terms, from the periphery to the center of the community of scientific practice (Lave & Wenger, 1991). The persistent representation of phenomena, combined with the spatial immersion, further promotes the goal of engaging all students; for all but the most dedicated non-participant, it eventually becomes easier to participate in an activity that impinges on his or her perceptual system all the time, wherever they look, than to ignore it, particularly when respected peers are engaged in the activity. Finally, by spreading interaction with the phenomena over multiple episodes we hope to take advantage of the potential of temporally distributed instruction over "massed" instruction with respect to recall and motor skill development (Donovan & Radosevich, 1999; Cepeda et al., 2006). It is important to note that effects of spacing and learning with respect to more complex material are less well understood (Dempster, 1989).

Persistence brings at least three additional benefits. First, by continually representing phenomena, we create the opportunity to reinforce the concept that, in nature, important state changes are not always synchronized to fixed schedules, that "things happen when they happen" (asynchronously with respect to the flow of instruction), and that scientists (particularly in observational sciences) are often at the mercy of events rather than the other way around. Second, persistence provides opportunities for "incidental" learning in much the same way that foreign vocabulary words adorning classroom walls may result in learning without explicit reference during formal instruction. We argue that the role of "student in the classroom" inherently demands the ability to attend to multiple concurrent threads of activity; at the same time that a teacher is speaking, a student might be working on a laboratory project, avoiding a spit-wad propelled in their direction, tracking the progress of a playground basketball game visible through the classroom window, and receiving an oral invitation to an after-school event from the student at the next desk. By adding an attentional channel that promotes curricular goals, we address the human need for variety and offer a potentially productive alternative to the normative instructional flow. Finally, by interleaving salient simulations with regular instruction, we surreptitiously expand students' opportunities to engage with additional science content.

Method

We investigated the alternative learning conditions with two cohorts of fifth grade students across subsequent years with the same teacher in a Midwestern U.S. elementary school. The teacher had previously conducted three RoomQuake units. The two cohorts were randomly assigned to condition with 27 students in the embedded condition and 18 students in the non-embedded condition. There was attrition of one student in each condition due to incomplete data.

Both classes received the same lessons during their regular science periods on Earth science concepts including the background on the Earth's layers and composition, the existence of tectonic plates, and the geological features that relate to the interactions of these plates.

Both classes also completed a series of 15 earthquake activities where they computed the epicenter of earthquake events from simulated seismograms. The main manipulation was in how the students engaged in these activities across the two cohorts. Students in the "classroom embedded, temporally-distributed" condition experienced a series of 15 simulated earthquakes ("RoomQuakes"), each presumed to occur within the physical space of the classroom. The simulation was effected by placing four 24" iMac computers around the classroom; each computer served as a simulated seismograph which depicted a continuously running strip chart recorder of ground vibration *for that exact location in the classroom*. Between events, the seismographs displayed simulated random noise; when a RoomQuake occurred, however, they traced out unique characteristic waveform (seismogram) corresponding to the expected vibration at their specific locations due to an event at a particular location in the classroom. The earthquake events occurred at unexpected times during the school day over a four-week period and were signaled by a low-frequency rumbling sound generated by the speakers in the computers.

In the non-embedded condition, students also worked with a series of 15 earthquakes, however, these were not simulated, nor were they presumed to be occurring in the physical space of the classroom. Instead students used the computers to access historical seismogram data from 15 earthquakes that occurred in Southern

California. For this condition, each computer represented a different seismograph station in Southern California and the four iMac computers were placed all in a row. The screens displayed snapshots of single seismogram readings and the students were able to go forward or backward through 15 snapshots representing the 15 different earthquake recordings. Students completed this set of activities as a single unit during their normal science time (it generally took a couple class periods to complete the set).

For each event in both conditions, students working in small teams were responsible for determining the epicenter and (Richter) magnitude of each earthquake and cataloging information about the event. By reading the seismogram at each seismographic station, students were taught how to determine the magnitude of the event, and the distance of the event from that station. They learned that earthquakes generate multiple waves that travel at different rates; and that the latency between arrival of two of those waves, P and S, is proportional to the distance between the earthquake and the seismograph. Magnitude can be determined by comparing event distance with graph amplitude. A reading from a single station, however, is insufficient to locate the epicenter, since it does not provide directional information. In order to obtain a solution, students needed to combine the distance information from multiple (at least three) stations through the process of trilateration.

In professional seismologic practice, trilateration is performed through the process of determining the common point of intersection among three or more circles, requiring a level of mathematical sophistication beyond that held by our learner group. To simplify this process for the students, the embedded class used calibrated dry-lines anchored at each of the seismographic stations to sweep out arcs reflecting the locus of solutions from the individual seismic stations until they found the location in the room where the endpoint of their measures coincided. Alternatively, in the non-embedded condition students used calibrated strings that were anchored at each of the seismographic stations on their large maps of Southern California to find the endpoint where all the measures coincided.

The unit also used workbooks that gave students practice with data recording methods and various kinds of symbolic representations of the data. Three types of public displays were also created. For the embedded group, the locations of the events were recorded by hanging Styrofoam balls from the ceiling at their epicenters, color-coded to reflect the event magnitudes. In the non-embedded group, however, students located the earthquake epicenters on a large map of Southern California and used color-coded stickers to reflect the magnitude. Two other public data representations were also maintained using colored sticky dots on large wall posters: magnitude frequency distribution (the number of earthquakes of magnitude 3, 4, 5 and 6) and a timeline of the events. The embedded condition had access to these representations through out the entire unit, while the non-embedded condition only saw them during science classes when working with the earthquake data.

Learning Goals and Measures

The learning goals of the RoomQuake unit were focused in three areas: (1) the acquisition of skill in authentic seismological practice, including the determination of event distance and magnitude, and the use of trilateration to determine event epicenters, (2) the development of an understanding of the distributional characteristics of earthquakes across the dimensions of space, intensity, and time, developed through student observation of the patterns reflected in the emerging historical record of events, and (3) an understanding of target Earth science concepts.

Skill in seismological practice. Following the unit, students were individually interviewed and asked to demonstrate their ability to read seismograms and compute epicenters. This included locating the arrival of the P and S waves, determining the distance between the arrivals of those waves, and determining the amplitude. They were also asked to find the magnitude of the earthquake using the data they had already collected from the seismogram. Additionally, students were asked to show the loci of potential epicenters using two different methods. First they had to find the epicenter by means of the method used in their class (either with strings in the classroom or strings on a map) and then as a transfer task they were asked to find an epicenter using three compasses on a piece of graph paper. We also probed declarative understanding of seismograms and trilateration through a series of multiple-choice prompts using a written instrument that was administered prior to, and directly following, the instructional unit.

Understandings of earthquake distribution patterns in space, time and intensity. Over time, collections of earthquakes exhibit characteristic distributions in where they occur (along fault lines marking plate boundaries), in when they occur (after-shocks follow large seismic events), and in their magnitude (strong earthquakes are less frequent than mild earthquakes). We probed these understandings through a series of multiple-choice prompts using a written instrument that was administered prior to, and directly following, the instructional unit. The same test was administered to both classes.

Structural and Causal Earth Science Concepts. Also included in the written instrument administered prior to, and directly following, the instructional unit we assessed understanding of Earth science concepts with a series of multiple-choice questions. The questions probed knowledge on topics including Earth structure and composition, plate tectonics, and the formation and location of geological features at plate boundaries.

Results

Pre/post Comparisons

The results of the pre- and post-activity assessments are shown below in Figure 3.

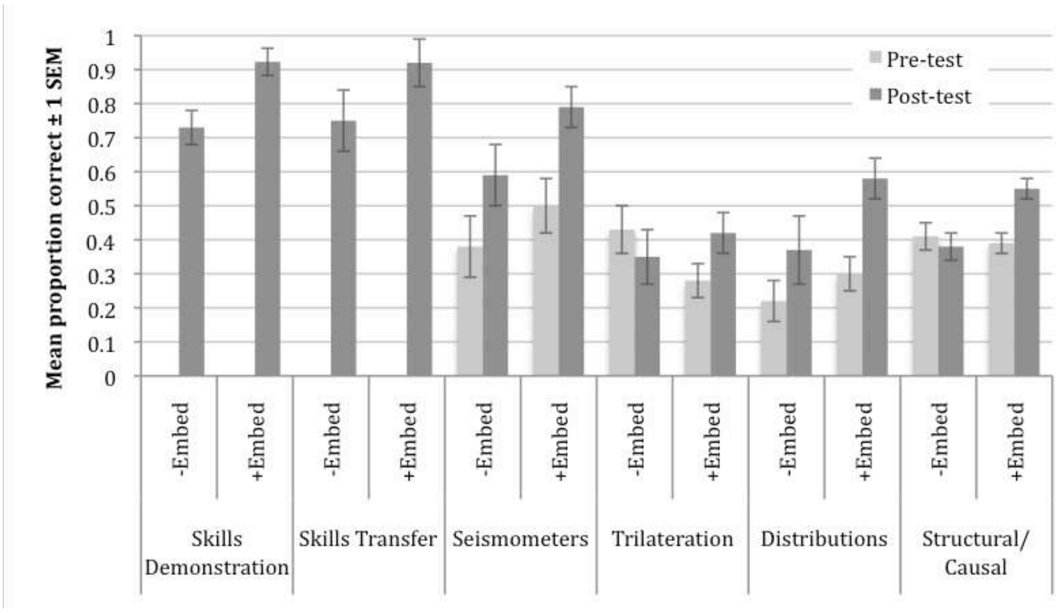

Figure 3. Performance on pre- and post-activity assessments for students in the embedded ("+Embed") and non-embedded ("-Embed") conditions: demonstrations of ability to identify earthquake epicenters, understandings of seismometers and their use, trilateration, earthquake distributions, Earth structures and causes of earthquakes.

Demonstration of Epicenters. For this task, students were asked to complete the epicenter tasks using the same methods as they had during RoomQuake (strings in classroom or on maps), as well as to compute epicenters using compasses on graph paper as a transfer task. The results were analyzed with a 2 (embedded, non-embedded) x 2 (same context, transfer context) repeated measures ANOVA. Neither the main effect for context, nor the interaction, were significant. However, the main effect for embeddedness was, F (1, 40) = 5.34, MSE = .125, p < .03. Students in the embedded condition outperformed students in the non-embedded condition on both practiced and transfer skill assessments.

For the remaining assessments, the results are analyzed with 2 (embedded, non-embedded) x 2 (pretest, posttest) repeated measures ANOVAs with pretest and posttest serving as the repeated measures.

Seismometer Use. There was a significant main effect for test time, F (1, 42) = 12.7, MSE = .10, p < .01. Students gained from pre- to posttest in their understanding of seismometers and their use. There was a marginal effect for embeddedness, as students in the embedded condition tended to have better understanding of seismometer use, F (1, 42) = 3.76, MSE = .15, p < .06. The interaction, however, was not significant, with similar performance gains across the two conditions.

Understanding Trilateration. There was no main effect for embeddedness condition or test time. However, the interaction of these variables did reach significance, F (1, 42) = 3.97, MSE = .06, p < .05 with students in the embedded condition showing greater gains than students in the non-embedded condition.

Earthquake Distributions. There was a significant main effect for test time, F (1, 42) = 18.4, MSE = .06, p < .01. Students in both conditions gained from pre- to posttest in their understanding of earthquake distributions. However, neither the main effect for condition, nor the interaction, reached significance.

Structural and Causal Earth Science Concepts. Overall there was a significant main effect from pre- to post-test on the understanding of Earth science concepts, F (1, 42) = 5.88, MSE = .02, p < .02, and a marginal effect for embeddedness condition, F (1, 42) = 3.79, MSE = .02, p < .06. These were both qualified by a significant interaction, with students in the embedded condition showing greater performance gains, F (1, 42) = 7.76, MSE = .02, p < .01.

Student interviews

An examination of the students' responses to the open-ended questions posed during the post-unit interview gives some additional insight into the features of the design that impacted their perception of the activity. In response to an item asking learners to describe "what they did" during the unit, students in the embedded condition focused strongly on the epicenter determination activity, while their non-embedded counterparts were much more likely to respond with descriptions of the other curricular activities included in the unit. To a question about the length of the unit intended to gauge student patience and boredom with the unit, "embedded" students were more likely to express a desire that the unit had been longer, with more "non-embedded" students voicing the opinion that it was too long.

Included in the interviews were several items that asked students to make comparisons between the condition that they experienced and hypothetical alternatives characteristic of the alternative treatment with respect to which would "help you learn about earthquakes and their causes better." In the following we will focus on the responses provided by the students in the embedded condition.

In one item, we asked students whether they would have preferred to have all of the earthquakes "back to back" on consecutive days (the "massed" treatment). In their responses, 22 of the 25 students interviewed indicated a preference for the temporally distributed approach, characterizing it as affording better opportunities for learning.

> Charley: *"The one we did, like which was when you guys did RoomQuakes because we took the time on each one so it helped me learn. I can't learn really fast."*

Asynchrony was perhaps the most appealing design element from the perspective of the learners, all 25 students saying they would learn better from the random earthquakes than ones scheduled at specific times, as suggested in another interview item. In their responses, they focused on realism and the excitement of not knowing when an earthquake was coming:

> Marty: *"It did, because if they were only during science time, that's not how they happen in real life, they only happen in real life, they don't have a certain schedule. In real life, they don't have a certain time that they are going to do it, so that gives you practice for the real world."*
>
> Robert: *"Being a mystery and at different times because, well like having a mystery, because for when there is a real earthquake coming you don't even know so you're just doing your work and it's always a mystery."*
>
> Danielle: *"Because of you did them all in a row in a couple days then we would know what to expect and when it would happen, but when you guys did it, it threw us off guard completely."*
>
> Charley: *"It just catches you in headlights, like you really don't know when it is going to come. It just surprises you."*

When asked whether the activity might have been more valuable as a learning activity if the trilateration work were done on a map rather than in the physical space of the room, 19 students preferred the latter, characterizing is as more "hands-on," more accurate, and more fun that a map version.

> Jacob: *"In the room because it would be better because it was turning our room into, say, California and we were having earthquakes."*
>
> Ariel: *"I think putting it on the room because it's, you can locate it more easily. Like it is easier to locate. Because you can like see where it is exactly like maybe you might, sometimes you could be off on a map."*

In their responses to this item, several of the students described the visceral impact of the experience in terms related to the presence construct.

> Abby: *"I like the way we did it here, it is like more real life because there are like RoomQuakes actually happening, it is not like we are reading what happens, we are actually in it."*
>
> Nguyen: *"Right here because I can feel it and I can do it right here."*

Jacob’s response anticipated the final question in our interview, which asked students if it would be better to characterize the earthquakes as “happening right here in your classroom” or “somewhere else, like southern California.” Over half the students favored the embedded treatment, saying that they could “experience more” and that it would be better for learning.

> Michelle: *“Well, I think always visualizing it, more experiencing it is better for people to learn because doing, being able to do it is not the same as being able to see it or hear it or because you will be able to interact with it and you'll be able to feel it. So, it’s like an actual earthquake. But, if it is in Southern California you can't feel it and you really don't know if it happened.”*
>
> Shaquille: *“Probably in by our classroom because if it is in another state or something, like, it's like you don't know how it is or how it's like and a RoomQuake is kind of like an earthquake and you can actually feel how it sounds like.”*

In contrast, six of the students preferred the hypothetical alternative treatment, characterizing is as “more realistic,” a better way to learn more about other places, and more fun to imagine being somewhere far way. The remaining students expressed no preference.

Discussion

While the number of subjects and variability of performance limited the power of the design, taken as a whole the study provides support for the claim that the spatial and temporal embedding elements employed in RoomQuake had a positive impact on learner outcomes. Students in the embedded condition consistently outscored their non-embedded counterparts on post-test assessments, with significant gains in several areas.

At the outset of the instructional units, none of the students had prior experience with the interpretation of seismograms or the use of trilateration to resolve distributed readings. Given the multiple opportunities for developing these skills, we were not surprised to see that students were proficient at these tasks at the conclusion of the units. We were surprised, though, at the significantly better performance demonstrated by the students in the embedded condition, since students in both treatments were given the same number of practice opportunities. The difference in performance cannot be attributed to a mismatch between the practice during the unit and during the assessment, since students used the same media for demonstrating the trilateration process (either calibrated dry-lines or strings on a map) that they had used in class in learning the skills.

What then, could account for the difference? While the classroom teacher organized students into teams for the epicenter determination activities and encouraged students to rotate roles within those groups, ultimately the choice of whether and how to participate rested with the individual learners. One possible explanation is that the opportunity to engage in the activity might have been diminished in the non-embedded case because it was more difficult to share responsibilities; determination of the epicenter, for example, required only a single student in the non-embedded condition whereas a pair of students (one anchored at the seismograph, one sweeping out arcs at the other end of the dry-line) was required in the embedded condition. An alternative explanation is that the motivation to participate in the non-embedded condition was damped by the fatigue or boredom induced by the massed scheduling, predictability, or less physical nature of the activity, or by the more restrained “impact” of the fruits of their labor on the accumulating inquiry evidence base.

The significant pre-post gains on the items related to seismometers and their uses, we believe, might be direct outcomes of the real-time and embodied nature of the embedded condition. In the embedded condition, students had the opportunity to witness the differential arrival of P- and S-waves at the simulated seismometer both visually (a change from “flat-line” to higher-amplitude graphs) and aurally (the rumble accompanying the arrival of the first wave). This may have reinforced their understandings of the seismometers as responsive instruments whose relative performance was dependent on their (differential) distances from the simulated seismic events.

Post-test performance on the trilateration items showed only weak gains for students in the embedded condition, and in fact a small loss for students in the non-embedded condition. We suspect that these results may be an artifact of the assessment items, which situated students in a transfer task requiring them to identify the loci of points defined by cartoon characters looking for one, two, and three items located around them, a task some students had difficulty in interpreting.

Students in both groups improved in their declarative understandings of the distributions of earthquakes, with students in the embedded group showing about twice the level of improvement from pre- to post-test assessment. Here we suspect that the salience of the representations of the empirical data (Styrofoam balls hanging from the ceiling and large posters with representations of the formative data at the front of the room), combined with the longer time course of the data collection process, worked to learners’ advantage in recognizing the emerging patterns.

The most surprising result was the significance of the difference in learning gains on the Earth science concepts (structure and causes of earthquakes) between the two groups. It is important to keep in mind that the learning activities associated with these concepts were identical in both classes, and were decoupled from the activity associated with the determination of event epicenters, in that the earthquakes themselves were merely the surface manifestations of underlying structures and processes not explicitly represented by our technologies.

While the "embedded phenomenon" strategy incurs minimal technology and materials costs, its use in classrooms demands significant preparation and scaffolding effort on the part of teachers. A necessary prerequisite to broader use of the technique is the existence of an evidentiary base that associates its use with positive learner outcomes across teachers and science content domains. The research presented here represents the first products of an ongoing counter-balanced multi-classroom, multi-domain research study that will be completed in 2010.

References

Collins, A., Brown, J., and Holum, A. (1991). Cognitive apprenticeship: Making thinking visible. *American Educator*, *6*(11), 38-46.

Cepeda, N J, Pashler, H, Vul, E, Wixted, J, & Rohrer, D (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin*.

Clancey, W. (1997). *Situated Cognition: On Human Knowledge and Computer Representations*. Cambridge, MA: Cambridge University Press.

Dede, C., Salzman, M., Loftin, R. B., & Ash, K. (1997). Using virtual reality technology to convey abstract scientific concepts. In Jacobson, M. J., Kozma, R. B. (Ed.), *Learning the Sciences of the 21st Century.* Lawrence Erlbaum.

Dempster, F. N. (1989). Spacing effects and their implications for theory and practice. *Educational Psychology Review*, 1, 309-330.

Donovan, J., & Radosevich, D. (1999). A meta-analytic review of the distribution of practice effect: Now you see it, now you don't. *Journal of Applied Psychology*, *84*(5), 795-805.

Dourish, P. (2001). *Where The Action Is: The Foundations of Embodied Interaction*, MIT Press.

Glenberg, A. (1997). What memory is for. *Behavioral and Brain Sciences*, 20, 1-55.

Glenberg, A. (1999). Why Mental Models Must Be Embodied. In *Mental Models in Discourse Processing and Reasoning*, Rickheit, G. and Habel, C. (eds). New York: Elsevier.

Johnson, M. L. (1987). *The body in the mind: The bodily basis of meaning, imagination, and reason*. Chicago University Press.

Lave, J., & Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge, UK: Cambridge University Press.

Lindblom, J., & Ziemke, T. (2007). Embodiment and Social Interaction: A Cognitive Science Perspective. In: Ziemke, Zlatev & Frank (eds.). *Body, Language and Mind. Vol. 1: Embodiment* (pp. 129-162). Berlin: Mouton de Gruyter.

Moher, T. (2006). Embedded Phenomena: Supporting Science Learning with Classroom-sized Distributed Simulations. *Proceedings ACM Conference on Human Factors in Computing Systems (CHI 2006)* (Montreal, Canada, April 2006), 691-700.

Moher, T. (2008). Learning and participation in a persistent whole-classroom seismology simulation. *Proceedings International Conference of the Learning Sciences* (ICLS 2008), Vol. 2 (Utrecht, Netherlands, June 2008), 82-90.

Thelen, E. (1995). Time-scale dynamics in the development of an embodied cognition. In *Mind In Motion*, R. Port and T. van Gelder, Eds.. Cambridge, MA: MIT Press.

Vygotsky, L. (1978). *Mind in society*. Cambridge, MA: Harvard University Press.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review*, *9*(4), 625-636.

Winn, W.D. (2003). Learning in artificial environments: Embodiment, embeddedness and dynamic adaptation. *Technology, Instruction, Cognition and Learning*, 1, 87-114.

Wisneski, C., lshii, H., Dahley, A., Gorbet, M., Brave, S., Ullmer, B., & Yarin, P. (1998). Ambient displays: Turning architectural space into an interface between people and digital information. *Proceedings International Workshop on Cooperative Buildings (CoBuild '98)* (Darmstadt, Germany, February 1998), 22-32.

Yantis, S. & Egeth, H. (1999). On the Distinction Between Visual Salience and Stimulus-Driven Attentional Capture. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(2), 661-676.

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