An edited version of this paper was published as:
Grimes, D., Warschauer, M., Hutchinson, T., & Kuester, F. (2006). Civil engineering education in a visualization environment: Experiences with VizClass. *Journal of Engineering Education, 95*(3), 249-254.

Civil Engineering Education in a Visualization Environment: Experiences with VizClass

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Abstract:

To bridge the gap between high-tech engineering practice and low-tech engineering pedagogy, *VizClass* was established: a university classroom environment incorporating a suite of digital whiteboards, a three dimensional stereoscopic display, and specialized software for engineering visualization. Through observations, interviews, surveys, and examination of student work, we investigated student and teacher attitudes toward VizClass and its effect on teaching and learning processes. Though the project is still under development, initial benefits include increased ability of faculty to visually explain complex problems, increased ability of students to conceptualize engineering problems, and increased engagement of students in after-class collaboration.

Introduction

Widespread recognition of the potential of visualization to enhance communication in collocated groups has led to several environments for visual offices and classrooms. Foremost among the visual office environments are the Interactive Workspaces Project at Stanford (iWork and iRoom, e.g., Johanson et al. 2002) and earlier work at Xerox PARC (e.g. the Tivoli system of Pedersen et al. 1993). The few visual classroom environments developed to date have not been designed specifically for engineering instruction, have relied on conventional 2D displays, and have had very different teaching tools and objectives than the VizClass project in this study. Examples include eClass at Georgia Institute of Technology (Brotherton 2002; Brotherton and Abowd 2004) and ActiveClass at the University of California in San Diego (Barkhuus and Dourish 2004; Ratto et al. 2003). The former was intended to relieve students from detailed note-taking in class; the latter was designed to allow real-time text messaging in large classes.

The NSF-funded *VizClass* project at the University of California, Irvine, is focused on developing a visualization classroom environment for engineering and computer graphics education. Display devices in the main VizClass classroom (VizClass I) include three 2D digital white boards (SmartBoards™) and a semi-immersive stereoscopic 3D wall display (Figure 1) (described in Hutchinson and Kuester 2004). Additional hardware components include an 8-node PC cluster, a touch screen display for controlling the PCs, and a surround sound system for data sonification. A second classroom (VizClass II) contains a single digital whiteboard. Unique VizClass software includes a sketch-based interface to a numerical solver and an interface to manage an 8-node PC cluster in VizClass 1. The two classrooms allowed us to compare a fully digital environment (VizClass 1) with a hybrid environment (VizClass 2).

Civil engineering, the specific discipline chosen for the experiment, is an appropriate subject area because the potential benefits of visualization are so far ahead of current pedagogical practice. This article focuses on student and teacher interactions with three aspects of the technology in courses over a three-year period:

- Three rear-projection touch-sensitive digital whiteboards (SmartBoards). Each digital whiteboard has a 72-inch diagonal surface that serves as both rear-projection display and touchscreen for direct input by finger touch or colored stylus. A wireless keyboard with a trackball also allows conventional indirect input.
- OpenSees (Open System for Earthquake Engineering Simulation): A command-driven, open-source simulation software framework for structural and geotechnical facilities, developed by the Pacific Earthquake Engineering Research Center, an NSF Earthquake Engineering Research Center (PEER 2005). It uses finite elements analysis (FEA) to calculate structural deformations, stress, and strain under various loading conditions. Although OpenSees is not a visual technology, it is included in the study because it was essential to the numeric solution of complex structural analysis problems.
- SketchFEA: A sketch-based visualization tool currently under development as part of the VizClass project at the University of California, Irvine.

Figure 1: VizClass1 – The 10-foot 3D stereo display is on the left. Two of the three 6-foot digital whiteboards display SketchFEA on the right. One shows a structure without lateral stress, and the other shows the warped structure under stress.

SketchFEA provides a graphics interface to OpenSees to allow rapid visual exploration of complex engineering problems. A user sketches a structural model with SketchFEA; OpenSees calculates stresses, strains, and deformations; and SketchFEA displays the deformed structure and other response parameters, as calculated under load (Kuester et al. 2005; Phair et al. 2004)

VizClass 1 also contains a passive stereo 3D display, which has been intensively used for three civil engineering projects: an animated visualization of the 1994 Northridge, California, earthquake; a hypocenter rendering project; and a stereo animation of a structure constructed using Lego building blocks. Figure 1 gives an example of the synergistic effect of multiple displays. The researcher displays the building under study on the stereoscopic 3D board on the left, while elaborating on a PowerPoint slide on a digital whiteboard in the center.

There is a common belief among engineering instructors that visualization tools enhance students' understanding of engineering principles and their application to problems (Naps et al. 2002; Naps et al. 2003). However, existing research gives little support for this belief. Prior studies of the effectiveness of visualization software in computer science education have yielded mixed results (reviewed in Hundhausen et al. 2002). In their meta-study of 21 visualization experiments in computer science, Hundhausen and his colleagues concluded that student engagement was more important than the type of visualization in contributing to learning. We found that visualization technologies enhanced engagement with the subject matter and the visualization technologies. This pattern of mutual reinforcement obscured distinction between the two.

This report covers four one-quarter civil engineering classes:

Quarter	Title	Classroom	Level	Students
Winter 2003	Finite Element Methods in Structural Engineering	Conventional Classroom	Graduate	8
Fall 2003	Finite Element Methods in Structural Engineering	VizClass 1 (3 SmartBoards)	Graduate	12
Fall 2004	Soil Dynamics	VizClass 1 (3 SmartBoards)	Graduate	9
Spring 2005	Finite Element Methods in Structural Engineering	VizClass 2 (1 SmartBoard)	Graduate/ Undergrad	23

Table 1: Civil engineering classes in this study

A principle investigator of the VizClass project and co-author of this paper (Hutchinson) taught all four classes listed above. Portions of this paper that refer to her were written by the educational evaluators (Grimes and Warschauer) from other departments. A co-investigator, also a co-author of this paper (Kuester), was the only other professor to use the VizClass facilities on a regular basis. We are preparing a separate analysis of four classes on computer graphics the latter he taught in VizClass 1. Our two parallel VizClass studies are mutually corroborating; we found similar patterns of use and similar reactions of students and professors in both cases.

<u>Methodology</u>

To investigate VizClass, we deployed a mixed-method exploratory case study to answer the following questions:

- How were VizClass technologies used in instruction?
- How did the learning process and learning outcomes change with the new visualization technologies?
- What were students' and teacher's attitudes toward the primary technologies: digital whiteboards, OpenSees, and SketchFEA?

Sources of data for the study included observations, interviews, surveys, and examination of student work. We observed each of the above-mentioned classes approximately six times. The first class, taught in Winter 2003, did not include any VizClass technologies and thus served for comparative purposes. Field notes were taken during observations, with a focus on the types of student-student and instructor-student interactions that took place during class, after class, and at laboratory sessions.

An interview of 15-60 minutes was conducted with the instructor shortly after the end of each of the above-mentioned courses, for a total of four instructor interviews. In addition, between two and twelve students from each class were interviewed in either individual or small group format. Students were selected for interviews based on their willingness to participate. Student interviews lasted anywhere from 5 to 60 minutes depending on the availability of the students and the number of participants. Interviews of the instructor and students focused on attitudes toward VizClass and perceptions of how it changed teaching and learning. All interviews were audio-recorded and transcribed. In addition to formal interviews, numerous informal conversations were held with the instructor and students throughout each course, with relevant points entered into field notes.

Brief student surveys were conducted at the beginning and end of each course and a more extended end-of-class survey was given to the class that used SketchFEA. Survey questions queried students' abilities to visualize engineering problems, their confidence and enjoyment in tackling such problems, and their interest in further research. Finally, we examined student homework assignments and projects and observed and took notes on student presentations.

The qualitative data were coded for basic patterns within each class, and then a cross-class analysis of qualitative and survey data was conducted to identify broader trends of VizClass utilization and impact. In the remainder of this paper, we will first examine how VizClass technologies were actually used and then summarize the impact such use had on teaching and learning processes and outcomes.

<u>VizClass Technologies in Use: Displays</u>

Digital whiteboards served throughout the study as enhanced whiteboards plus projectors. Primary uses were PowerPoint slides and drawing. Secondary uses were animations, other instructional programs, and Web browsers. Although users needed the remote keyboards for tasks that required typing, they almost always gravitated toward direct interaction with the large touchscreen when typing was not necessary.

The students and the instructor enjoyed the brightly colored digital ink and the ability to have three simultaneous displays in parallel (four displays counting the 3D projector). Unlike the instructors in the eClass project at the Georgia Institute of Technology, the instructor in VizClass chose not to capture class notes for later posting on the web. Although several students recognized the potential for displaying the instructor's classroom notes on the Web, they said that after-class access would be no more than a minor enhancement, an attitude that is consistent with the low level of Web use in eClass.

The digital whiteboards and 3D display in VizClass 1 were each driven by a separate PC in the 8-node cluster. Logins to the 2D and 3D displays were managed through interface software accessed through a small LCD touchscreen near the entrance to the room (Groeneveld et al. 2004) (not to be confused with the large touchscreen of each digitial whiteboard).

The digital whiteboards came with proprietary software that allows users to write over computer displays such as PowerPoint slides. The fact that the resulting overlays were not integrated with the computer display introduced presentation challenges, and students were left with the impression of unreliable software. Once the instructor carefully drew a 3D diagram, only to have it disappear as soon as it was complete.

Program control was also unpredictable. PowerPoint sometimes changed slides unexpectedly. The students and the instructor often joked about these and other bugs and adapted to them quickly.

Students in VizClass 1 frequently stayed after class to discuss projects and homeworks and to experiment with the digital whiteboards. Their prior experience with Microsoft Windows shaped their expectations for the interface, but they easily made adjustments. When, for example, they couldn't find the right mouse button, they usually proceeded without comment as if nothing were out of the ordinary.

A survey given to the last Finite Element Methods class asked students to assess the value of three of the VizClass technologies. On a scale of 1 to 5, 1 was "very negative," 3 was "neutral," and 5 was "very positive." As Table 2 shows, in response to questions on how the digital whiteboard affected their ability to visualize engineering problems and their enjoyment of the same, the average responses were 3.5, or halfway between "neutral" and "slightly positive." The enrollment was too large for VizClass 1, so this class used VizClass 2, which had only one digital whiteboard.

	How did each of the following affect your *ability to visualize* engineering problems?		
	SmartBoards	SketchFEA	OpenSees
Average	3.52	3.22	3.39
Std Dev	0.59	1.00	0.89
Confidence	$p < .01$	Not signif.	Not signif.
	How did each of the following affect your *enjoyment* in solving engineering problems ...?		
	SmartBoards	SketchFEA	OpenSees
Average	3.48	2.91	3.30
Std Dev	0.73	1.02	0.97
Confidence	$p < .01$	$p < .05$	$p < .05$

Table 2: Students' Assessments of VizClass Technologies for visualization and enjoyment of solving engineering problems (N = 23). Students were 11 undergraduates and 12 graduates in the Spring 2005 FEM class.

(5-point Likert scale: Very negative = 1; Slightly negative = 2; Neutral = 3; Slightly positive = 4; Very positive = 5. Confidence levels are based on a norm of 3.0.)

Graduate students rated the digital whiteboards more highly than undergraduates in terms of enhancing their ability to visualize engineering problems. The averages were 3.8 and 3.2, respectively. In response to a question on how the digital whiteboards affected their enjoyment in solving engineering problems or watching class presentations, a similar difference applied: 3.9 for graduates vs. 3.2 for undergraduates. In both cases a t-test showed the difference to be significant at the 1% level ($p < .01$).

Table 3 summarizes interviews and surveys of students in two classes in civil engineering. For these courses “VizClass” was nearly synonymous with the three digital whiteboards. Although they were quick to note bugs in the new interface software for the SmartBoards, it is noteworthy that none of the students expressed negative opinions in response to the questions in Table 3. In general, they appreciated the digital whiteboards’ clarity and vividness, and felt VizClass contributed marginally to understanding the course material, stimulated greater excitement in the course, and increased their ability to visualize engineering problems.

Question	Response		
	Positive	Neutral	Negative
Opinion of VizClass	12	1	0
Helped grasp course materials	6	6	0
Increased excitement in course	6	4	0
Increased desire to do research	4	5	0
Increased confidence in ability to solve engineering problems	2	8	0
Increased ability to visualize problems	7	5	0

Table 3: Summary of responses to interviews with 14 students (2 students in the Fall 2004 Soil Dynamics class and a focus group of 12 students Fall 2003 Class in Finite Element Methods). Positive responses ranged from slightly positive to strongly positive. No negative responses were reported to any of the questions above. However, there were many complaints about software bugs in SketchFEA and the SmartBoard notepad software, and a few complaints about usability of OpenSees. Many participants expressed no opinion on several questions.

These survey and interview results compare favorably to results obtained from the surveys of students taking the Finite Element course in the traditional classroom in Winter 2003. For example, analysis of the beginning- and end-of-quarter survey responses in that Winter 2003 class indicates no perceived improvement by students of their ability to visualize engineering problems or any increased desire by students to conduct research using finite element methods.

In evaluating the benefits of VizClass, the instructor expressed enthusiasm for the digital whiteboards. At the end of the first Finite Element Methods course in VizClass she said, “After I figured out how to synchronize my lectures, my PowerPoint/note style lectures, my exam scores were higher this year overall and I covered more material.” When the second Finite Element Methods class moved from VizClass 1 with three digital whiteboards to VizClass 2 with only one, she wrote mostly on the regular whiteboard because of limited space on the digital whiteboard.

Minor disadvantages of the digital whiteboards were a need for low-tech backup (in the form of a conventional whiteboard), an imprecise digital eraser, and the need to sit in order to comfortably use the remote keyboards. Class participation was about the same with digital whiteboards and regular whiteboards, but after-class collaboration was greater with the digital whiteboards, as discussed further below.

VizClass Technologies in Use: Engineering Visualization Software

OpenSees was used in the last three offerings of the Finite Element Methods course. The sketch-based software for the numerical solver was introduced to the FEM class in the third year of the project in Spring 2005.

The instructor and her students report that OpenSees is very powerful, but it is difficult for novices to use. It requires laborious calculations to prepare the inputs (mesh coordinates), it has a cryptic command-line programming interface, and the documentation is unpolished.

To overcome the above difficulties and to allow quick, intuitive visualization of static structural stresses, a graduate student has spent two years developing SketchFEA, a sketch-based front-end to OpenSees (see Phair, Hutchinson, & Kuester 2004). The user draws a structure and the loads that he wants to model, SketchFEA calculates the mesh coordinates for OpenSees, and OpenSees returns the nodes of the deformed structure to SketchFEA, which draws the deformed structure.

Students learn SketchFEA by first modeling simple structures and loads, such as a single-point weight on a beam, and progress toward more complex problems. SketchFEA also warps images with superimposed structures. For example, if one draws the main structural elements of the Eiffel Tower over a picture of the tower and applies a strong horizontal wind load, the picture is warped in proportion to the wind pressure.

When introduced to the Finite Element Methods course in the Spring of 2005, SketchFEA had significant drawbacks. It was limited to 2D, with 3D planned in the next two years. Computation was slow because it was written in an interpreted language, Python. It was designed for use with a digital tablet, which few students had. Updates were frequent. Most important, bugs plagued some functions, especially the stylus tool, and behavior was very machine-dependent; On the last day of the quarter the author tried it on four Windows machines, and each of them misbehaved in a different way.

In response to the survey questions on how OpenSees affected their ability to visualize engineering problems and their enjoyment of such problems, students rated OpenSees about 3.3 and 3.4, respectively -- slightly above neutral (Table 2). The average responses on how SketchFEA affected their ability to visualize was 3.2. However, enjoyment of SketchFEA averaged only 2.9, slightly below neutral. Unreliability clearly detracted from students' enjoyment of the program. Nevertheless, according to the instructor, all but four of the students were able to solve homework problems with it, and several students spoke highly of the intuitive visual interface and its great potential time-savings when fully functional and debugged.

In terms of their enjoyment of SketchFEA , graduate students and undergraduates differed by a wide margin (3.5 for graduates vs. 2.4 for undergraduates). In other words, the graduates tended to like it and the undergraduates tended to dislike it ($p < .05$). This finding parallels the above-mentioned more positive assessments by graduate students of the digital whiteboards. However, it was disappointing to the developer of SketchFEA, who had hoped his graphics interface would make FEA and OpenSees easier for novices.

The difference in the two groups' perceived value of the technologies corresponds to an apparent difference in their levels of engagement with the technologies and the class in general. Graduate students reported spending more time on homeworks (not statistically significant), more time using SketchFEA ($p < .05$), and more time on OpenSees (p. < .01).

Projects by two graduate students in the last FEM class illustrate different ways of integrating OpenSees with visualization software. In the first project, the student built a 2D model of a shear wall building out of wooden coffee stirs and measured its deflection when subjected to a horizontal load. He then sketched the model with SketchFEA (Figure 2a), applied the same load to the computer model (Figure 2b), and compared the outcome with his physical mock-up. He also used SketchFEA and OpenSees to analyze three bracing options: shear wooden bracing, plywood shear sheathing, and shape memory alloy wires.

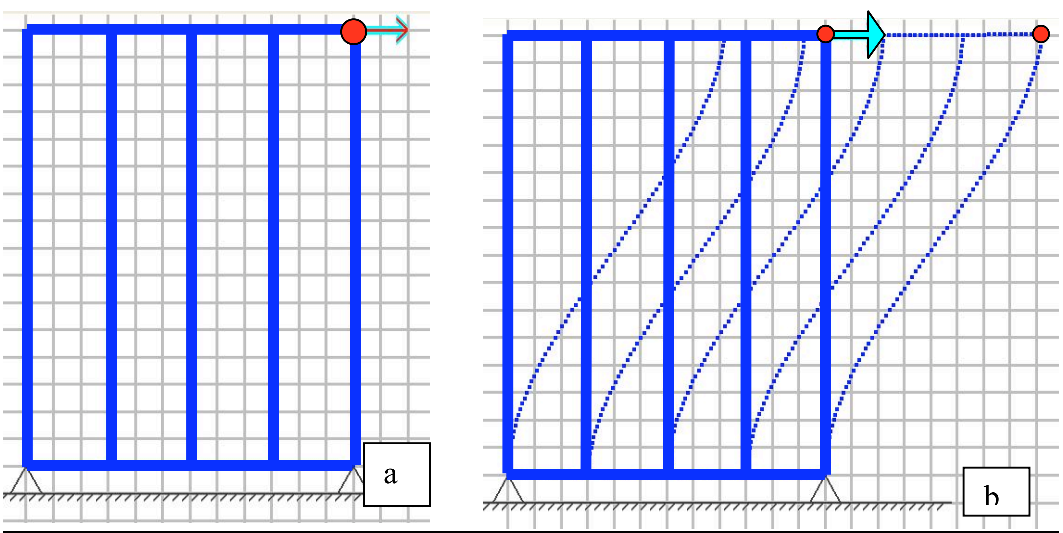

Figure 2: Model in SketchFEA (a) before and (b) after applying horizontal load.

The second project was a visualization that would not have been feasible without a numerical solver to handle the thousands of degrees of freedom and associated large matrices sizes. The student used OpenSees to model a geodesic dome, then analyzed the deformation under inward (Figure 3a) and outward (Figure 3b) internal pressure. He experimented with different mesh discretization settings (varying coarseness) and modified an open source graphics package to pre-process the mesh details for use in OpenSees.

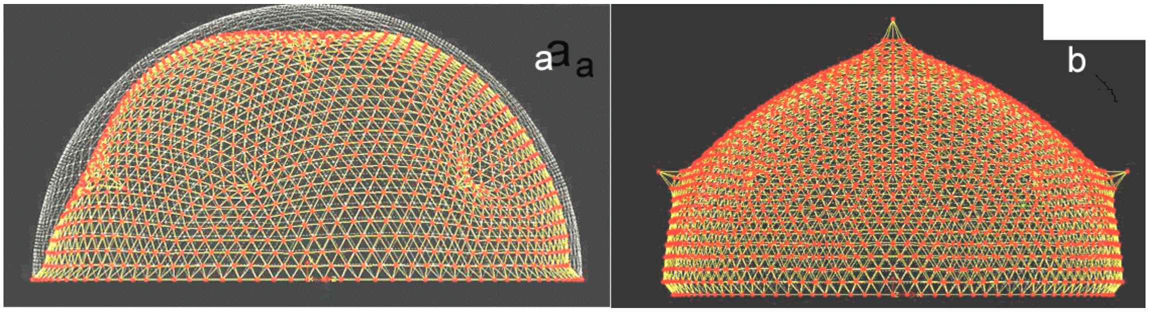

Figure 3: Geodesic dome under inward (a) and outward (b) internal pressure.

Impact on Teaching and Learning

The educational impact may be summarized in terms of the teaching process, the learning process, and the learning outcomes.

Teaching process. Each of the three major visualization tools affected course structure in different ways. The digital whiteboards encouraged reorganization of presentations very much as an LCD projector would, i.e., around PowerPoint slides, animations, and other computer-based displays. OpenSees, both by itself in the second Finite Element Methods class and in conjunction with SketchFEA in the third one, empowered students to solve more sophisticated problems than they could address with manual computations. These software packages became central to the homework and class projects.

Differences in classroom size, enrollment, and visualization tools contributed to differences in instructor-student interactions in the two VizClass classrooms. For example, VizClass 1, with seating for only 12 students, was more conducive to seminar-style teaching, especially when the instructor sat down in a conscious and effective effort to draw students into discussions. VizClass 2, with seating for over 40, required the instructor to stand in order to be heard at the back of the room.

Learning process. There is widespread recognition that cooperative learning enhances critical thinking, reflective thinking, social skills, and motivation (reviewed in Smith et al. 2005). The digital whiteboards invited impromptu after-class discussions in small groups who gathered in front of the boards. Protocols for sharing access to the large touchscreens emerged spontaneously, and were negotiated with body language more than words. Participation was more balanced than with comparable discussions around a laptop or desktop computer, where only the user at the keyboard can control the display. In some cases, three students collectively drew, each with a different colored stylus. Visibility was also more equal than with a small screen. After-class collaboration was frequent in the two classes taught in VizClass 1, occasional in the class taught in VizClass 2, and rare in the class taught in a conventional classroom. Beyond the immediate after-class period, student-student collaboration at the digital whiteboards also took place during one or two open lab hours set aside a week. Several students who took classes in VizClass 1 commented in interviews that they wished it were open more extended hours for their use.

The only significant negative reactions from students related to software bugs, mostly in SketchFEA and the interface software in VizClass 1. The introduction of under-tested software into fast-paced classes revealed a tension between three conflicting goals. First, from a development perspective, early introduction of these tools provided an ideal test bed to accelerate development so that future classes might enjoy more robust tools. Second, from a conventional learning perspective, the unpredictable nature of the software distracted attention from course goals. And third, from a broader learning perspective, the students gained valuable experience in dealing with fast-evolving software; the programmers and professor provided positive role models for efficacious response to bugs. (For a discussion of modeling and self-efficacy in education, see Bandura 1997.)

Learning outcomes. Although the students complained about bugs in SketchFEA, most used the software successfully and learned from it. The instructor believed that the VizClass technologies added to her ability to teach and to her students' ability to learn. As she explained in an interview, "It helps them visualize numerical models of physical systems." A few students blamed bugs in SketchFEA for their failure to complete the final homework. Since none of them availed themselves of help from the professor or teaching assistant, their lapses may reflect a last-minute start on the homework as much as buggy software.

The instructor had taught the finite element course twice without OpenSees and twice with it, but never before with SketchFEA. She reported that when SketchFEA was added to OpenSees, students demonstrated better understanding than students in the prior courses. They asked better questions and engaged in better discussions, and all of them were able to derive a numerical model for a physical system. The latter was often a major stumbling block for engineering students. None of her four prior groups of students had achieved 100% success in reaching this threshold. In addition, she said the final projects in the most recent FEM class were superior to any of her prior classes'. Although this group of students may have excelled anyway, their success supports the merit of further pedagogical experiments with with SketchFEA.

In interviews and surveys, some students characterized the VizClass tools as "cool," "fun," or "high-tech," but qualified their approval by saying they added little to their learning. Such views may have been based on a conception of learning that underlies our exam-based educational system, i.e. the idea that learning is abstract, individualistic, and objectively measured by recall of facts and formulas to solve stable, well-defined problems. In contrast, a multi-disciplinary body of literature argues that the type of learning needed for professional success is situated, collaborative, and subjectively applied to solve unstable, ill-defined problems (see, for example, Lave and Wenger 1991; Schön 1983; Wenger 1998). The latter conception of learning places more weight on increased engagement and collaboration, qualities we observed in VizClass, even among students who saw no learning value in the VizClass tools.

The instructor's assessment of learning outcomes was more strongly positive than the students'. Her view was loosely corroborated by indications of student engagement, including careful attention to detail in the homework and projects, student reports of greater than usual time spent on homework, and thoughtful questions and enthusiastic peer discussions after class. In addition, the last two student self-assessments summarized in Table 3 indicate increased self-efficacy with regard to visualizing and solving engineering problems. (Self-efficacy is belief in one's ability to perform in certain areas. It is a valuable predictor of future performance over a broad spectrum of social, intellectual, physical, and professional skills.) (Bandura 1997). Although individual questions and answers are subject to debate, the collective import of the answers is favorable.

Limitations of our assessment of outcomes include possible Hawthorne effects (subjects' responses may be affected by the attention they received as study participants) and the small numbers of students and classes involved. The instructor's natural enthusiasm, amplified by her central role in the VizClass project, would be hard to replicate.

Conclusion

Rigorous, randomized experiments are a rarity in education because of resource limitations, conflicts between assessment and pedagogical objectives, and difficulties measuring intangibles like motivation and collaboration. As an example of the conflict between assessment and pedagogical objectives, it was not feasible to randomly assign students into two parallel sections taught by the instructor, one in VizClass and the other in a traditional classroom. The closest feasible approximation was to compare classes in VizClass with earlier iterations of the same course by the same instructor. Exam questions varied in each iteration, so quantitative comparison of learning outcomes between iterations was impossible. Not only was a randomized experiment infeasible, it would have disturbed the natural setting, and would have been unlikely to reveal the qualitative changes we have noted. (e.g., Lincoln and Guba 1985)

This study has relied on three sets findings in the assessment literature. The first set supports the general credibility of teachers' judgments of academic achievement (Hoge and Coladarci 1989). The second set, already mentioned, supports self-efficacy as a predictor of performance success (Bandura 1997). The third set identifies engagement as a key factor in learning outcomes (e.g., Hundhausen et al. 2002; Naps et al. 2002; Smith et al. 2005).

The most salient qualitative finding of this study was increased collaborative engagement when students spontaneously gathered around the digital whiteboards after class and during open lab sessions to collectively analyze problems. The engagement principle (active engagement leads to improved learning) was also evident in the students who wrote the custom VizClass software, those who wrote engineering applications for the 3D stereo display, and the FEM students who went furthest in exploring analysis and visualization software for their projects.

Given the reported failure of many visualization projects to improve learning, we are encouraged by the preliminary results reported here, especially given the embryonic state of the visualization software. Homework and projects in the last Finite Element Methods class integrated active visualization with numerical models of real engineering problems, thereby achieving a primary project goal.

The most far-reaching features planned for VizClass were only partially implemented at the end of our three-year study period. However, the hardware environment had stabilized and the major new software components had reached a preliminary operational state. Future classes will be able to make fuller use of the numerical solver and the combination of 2D plus 3D displays as they continue to evolve. Equally important, the researchers continue to refine their integration of the new technologies into instructional design, so that students may make fuller use of the new visualization tools.

It is widely acknowledged that visualization technology is a mediator of learning and communication in general. In this study changing the technology changed the nature of learning and communication. The results suggest a modest but noteworthy shift in focus from hand computation to higher-order conceptual skills.

Acknowledgments

This project was funded by the National Science Foundation Combined Research Curriculum Development program under Grant Number EIA-0203528, where Dr. Anita LaSalle is the program director. We also acknowledge the support through the California Institute for Telecommunications and Information Technology (Calit2), the Henry Samueli School of Engineering at the University of California, Irvine (UCI); and Research and Graduate Studies at UCI. We also thank the students that participated in the surveys, and especially Mr. Ben Langhorst and Mr. Andrew Good, whose projects are presented in Figures 2 and 3. Most of all, we thank Mark E. Phair, author of SketchFEA and astute reviewer of this article.

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