development strategy in the context of our MUVE science curriculum. □

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The Classroom as "Living Laboratory": Design-Based Research for Understanding, Comparing, and Evaluating Learning Science Through Design

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Design-based research can also be used to convert a classroom into a living laboratory providing educational researchers and practitioners with an opportunity to study pedagogical implementations in local contexts. This article describes how learning science through design, a pedagogical approach that integrates the learning of science and programming, was compared and evaluated in various aspects over the course of four years. Design-based research generated implications not only for the improvement of educational practice but also for creation of sustainable educational reform.

Design-based research has often been described as an effort to bring the laboratory into the classroom, addressing the complexity of learning situations. While laboratory research affords the opportunity to control many features of the environment, task, and learning process that might impact students' performance,

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ethnographic research offers access to interactions of students and teachers in an authentic learning context. The classroom as a "living laboratory" approach offers a combination of both and promotes the idea of the classroom as a living culture that can be seeded for studying learning in context while maintaining control of critical features.

Very few proponents of design-based research have used classrooms as living laboratories to study the same participants' learning over extended time periods as they become more experienced in what they are doing. Students and teachers regularly come to class—day after day, year after year—and thus provide a learning environment accessible for systematic interventions and extended observations. In this article, I describe and analyze a curricular intervention called "learning through design." Elementary fourth and fifth grade students work in teams designing and implementing software that teaches younger students in their school about a science topic. Teams are composed of both students experienced in the project task and those new to the activity. In addition, many students have participated in these projects as third graders, the intended audience for the software, before moving into the software design activity the following year.

Our design-based research approach used three phases, which examined different aspects of students' learning through design:

- In the first phase, we implemented a classroom model of learning through design. Our goal was to understand different aspects of students' interactions during the three months of project activity. We analyzed group conversations at beginning, middle, and end points of the project, as students were planning and finalizing their software and science designs. In addition, we paid attention to how collaborative interactions were structured between experienced and inexperienced members of the project team.
- In the second phase, we examined in more detail one critical feature, the role of prior experience in collaborative interactions. We compared two classrooms taught by the same teacher differing in one aspect: the composition of experienced and inexperienced members in a team. In the focus class, we had students experienced with the approach of learning science by design in teams together with inexperienced students, while a comparison class following the same curriculum had teams with inexperienced students only. This comparison allowed us to identify collaboration approaches pertinent to experience and to assess their impact on other project variables, such as students' science and programming learning. We focused our analysis on "helping interactions," identified in the collaboration literature as a key ingredient for improved learning.
- The third and last phase was to evaluate the long-term impact of learning through design: how students who participated in this project for four years came to understand their own learning experience as software designers. We interviewed students about their participation and roles in each of the project years.

Design-based research provided an appropriate methodology to address all these goals. Our approach was an intervention and an observation at the same time. The purpose of our effort was not to prove that learning through design was an effective pedagogical approach because previous research had addressed this question (Harel, 1990). Our focus was on identifying those features that impact the effectiveness of learning through design.

Theoretical Background

Constructionist learning theory (Papert, 1980, 1991) provides the theoretical umbrella for the pedagogical approach of learning through design. It posits that learning happens best when learners are engaged in creating artifacts representing their ideas. Learning artifacts can be computer programs, robotics constructions, games, or writings that are open to examination and discussion by and with others. Learning science through design, as described here, draws its inspiration from the instructional software design project (Harel & Papert, 1991) in which students created instructional software to teach younger students about fractions. The learning artifact, the instructional software, provides students with an opportunity to reformulate their understanding and to express their personal ideas and feelings about fractions in graphics and programming. The intended users, the younger students in their school, provide the learners with an audience and social relevance. The collaborative design of software and the apprenticeship arrangements were new features of the learning through design project not investigated in previous studies.

Learning through design belongs to the larger family of project-based learning approaches that propose integrative, authentic, long-term curriculum units for learning mathematics, science, or social studies (e.g., Blumenfeld, Soloway, Marx, Krajcik, Guzdial, & Palincsar, 1991; Brown, 1992). Many of these project-based and design-based approaches involve the use of technological tools to help students in their inquiry and artifact construction. In learning through design there is an explicit focus on learning programming, not for its own sake, but to support the learning of other subject matter. This approach addresses many of the key shortcomings identified in previous research on programming in schools (for an extensive review, see Palumbo, 1990). Programming, or software design, includes the creation of socially meaningful artifacts, such as instructional software that is familiar to and used by students and that is integrated with other classroom topics.

The collaborative interactions between experienced and inexperienced team members address theoretical and practical issues of situating apprenticeship learning in schools (Collins, Brown, & Newman, 1989). Some researchers have argued that apprenticeship is problematic in school contexts (Lave & Wenger, 1991), while others have seemingly accepted the impossibility of locating apprenticeship within the classroom walls and have instead opted for placing students in laboratory apprenticeships with practicing scientists (Hay & Barab, 2001) or for appropriating scientists' tools for use in classroom communities (Edelson, Pea, & Gomez, 1996). In all these diverse efforts, however, there is one constant: Teachers and scientists are always placed in the role of experts, or old-timers, and students are always beginners, or newcomers. At no time are students full practitioners in the learning contexts and cultures they inhabit.

In learning science through design, we have attempted to create a full-fledged model of apprenticeship learning within the school context, using existing mixed-grade arrangements. Students start as third graders evaluating software designed for them. In fourth grade, these students work together in teams with experienced fifth graders designing science software for third graders. Finally, students become fifth graders themselves, taking on the role of guiding and socializing the new cohort of fourth graders (previous third graders) into learning through design project activities (described in more detail in the next section). This apprenticeship model implemented in learning science through design projects has a reproductive character and provides learners with connections to the past and future of their activities.

Implementation and Research Methods

A "typical" learning through design project is comprised of eight to ten teams with students experienced (i.e., fifth graders) and inexperienced (i.e., fourth graders) in the project approach. Students work in a classroom that consists of different areas: a "rug" area in front of a whiteboard and seven table clusters, each of which has Macintosh PowerPC workstations connected to the Internet. In addition, there are four other computers in the classroom against the walls, one of which is used mostly by the teacher to demonstrate projects or activities on a large-screen TV display; the other serves as a scanner station. All the computers contain software, which students use to program their science software.

In general, the class spends 75 minutes, four days per week, on science and software design-related activities. Each project starts out with an all-class discussion in which students generate the questions they have about the science topic. Parallel to the generation of research questions, all teams participate in a three-hour introduction to basic graphic and software design functionalities of their programming environment. During this introduction, the teacher asks the old-timers to help newcomers learn the basic programming functions while creating their first animation.

Several kinds of evaluation activities take place throughout the project. Twice, at weeks five and eight, a group of 14 third graders comes to visit and use the developing instructional simulations. The student instructional designers conduct these "usability sessions" themselves. Before the usability visit, design teams meet and discuss the questions they want to ask the third graders in regard to their liking and understanding of the software. Informal evaluations and demonstrations also occur throughout the project, as students visit different teams' workstations to view others' computer screens. At the end of the project, the whole class meets to generate criteria for final software evaluations and a list of evaluation questions. Students' participation in all of these activities provides the context for their integrative learning of software design, collaboration, project management, and science.

We used a variety of methods to document and evaluate student learning, classroom activities and group work. All students took pre- and post-tests about their science understanding and programming knowledge. Student teams were videotaped as they met during class time to plan, research, and implement their software. Each team was captured for at least 30 minutes on tape approximately once a week. We videotaped the class session at the end of the project in which students generated criteria for the final evaluation activity, and we collected all the final evaluations and student comments. Finally, we also interviewed all the students at the end of the project. The interview questions varied depending on whether students were newcomers or old-timers to the project. The questions asked students about their design project experiences by examining their collaborative and individual contributions, the development and application of project management strategies, their generation and implementation of research questions and their expectations for prospective design projects. All interviews were videotaped and then transcribed in preparation for coding. In addition, case studies were prepared on individual teams to follow their interactions over time.

The Findings

The data collected from several years of learning through design projects provided us with a rich and systematic understanding of project dynamics, the impact of previous experience on collaborative interactions, and students' perceptions of their own learning. These aspects are described below.

Understanding Learning Through Design. In this phase of our design-based learning approach, we implemented a classroom model and studied its development. One of our analyses focused on students' collaborative planning of science software designs (Marshall, 2000). We found that the content of planning discourse shifted according to the demands of the project from a focus on design to a focus on completion. The experienced team members played a crucial role in addressing key issues by referring explicitly to their previous project experience. We then analyzed the science content in planning discussions, addressing a key question on whether the integration of learning science is part of students' concerns (Kafai & Ching, 2001). We found that students indeed addressed science content in their planning discussions, but did so in more depth when discussing the idea and content of software screens. The level of science content and discussion also varied at different time points in the project, with most of the science-oriented discussions taking place in the early planning sessions. Again, the experienced team members not only initiated, but also expanded conversations around science topics. This first set of analyses illustrated the important role that more experienced students played in their teams but left open a key question, on whether the age of students (fifth graders) or prior project experience was responsible for this performance.

Comparing Learning Through Design. In the second phase, we compared two classrooms taught by the same teacher differing in one key aspect: the composition of experienced and inexperienced team members (Ching, 2000). In the focus class, we had students experienced with the approach of learning science by design in teams together with inexperienced students, while a comparison class following the same curriculum had teams with inexperienced students only. The analyses from three different vantage points—ethnographic study of apprenticeship interactions in teams, interviews about students' perceptions about their role as team members and those of others, and a pre- and post-test comparison of science and programming knowledge—revealed a clear pattern: Previous experience, and not age, was a decisive factor.

Students' apprenticeship interactions were structured very differently in teams with experienced members: Students adopted more collaborative, shared modes of interactions when working with new members in their teams; and they also allotted more room for making mistakes, while still monitoring the progress of inexperienced team members. In the comparison class, the older students tended to control most interactions around the computer, leaving little room for incoming students to develop their own experience. When students were asked to articulate their own roles and those of others in the team, the differences between experienced and inexperienced students reflected their working arrangements: Students in the focus class had significantly richer understanding of the roles of experienced students when compared to students in the comparison class. Students' roles included cognitive (i.e., "knowing more programming"), social (i.e., "providing more help"), and affective (i.e., "knowing how it felt being a beginner") components.

These differences also appeared in other aspects of project performance. The number of software pages created by each team revealed a striking difference: In the focus class, teams created an average of 19.75 pages, whereas teams in the comparison class achieved less than half, an average of 7.85 pages. This investigation of how well students learned Logo programming produced some interesting patterns. A general linear model analysis of students' Logo test scores revealed a significant difference between pre- and post-test scores, as well as significant differences between class and grade level; there were no significant gender differences.

Evaluating Learning Through Design. The third and last phase was to evaluate the long-term impact of learning science through design by examining students' perceptions of their own performances in the learning through design project (Kafai & Roberts, 2002). We asked students to review their project experiences as third grade software users, fourth grade newcomers to design, and fifth grade old-timers in software design. Those students who had been software users as third graders mentioned aspects such as, "It was really confusing because all these people were like fifth graders and I was a third grader and they had really, like, tough subjects and I just looked at their animations. It was really new. I thought like, 'man, I want to do that when I get into fourth grade'...I got a little glimpse of what I would be doing in the next two years."

When students then moved into fourth grade as newcomers, all students mentioned the knowledge of the programming language as the most prominent aspect of their experience being software apprentices, "when I didn't know how to work Logo, it was kind of hard," followed by social differences, "I had to sort of learn on my own and from other people," and affective aspects such as "but once I learned it, then I realized it was really fun to work with [Logo]."

When students reviewed their fifth grade experience, their increase in knowledge of the programming language was mentioned as frequently as their social interactions when they were able teach other people to program, "It was better because I kind of show people because I was the one who knew what to do. Instead of just being the one who was taught, I could teach people." Whereas affective aspects were only mentioned by two students such as, "[b]ut the fourth graders kind of have more needs. They're still kind of beginners in this huge learning process that when I was a fourth grader I didn't even get. So I could feel exactly what they were feeling. But also one of the good things about the higher expectations is once you meet those expectations, you're kind of a full [sic] fifth grader."

Further analyses of the learning through design project covered related aspects: Team contributions to the multimedia design products (Kafai, Ching, & Marshall, 1997), student software designers as users and evaluators of instructional software (Kafai, 1998), gender differences in access to design activities (Ching, Kafai, & Marshall, 2000), student perceptions of their social networks in repeated design projects (Kafai, 2002), and student and teacher evaluations of final software products (Kafai & Muir, under review). These findings from our design-based research approach provide critical input for modifications of the curricular intervention. They suggest that classroom and team discussions can be focused to address both programming and science issues. Further studies are needed on whether such directives provided by the teacher in the form of worksheets, discussion prompts, or feedback can accomplish such integration.

Implications

The findings from our design-based research approach have several implications for theory, practice, and policy. Design-based research provided an appropriate approach to examine the nature of students' learning of a complex task on a daily basis over several years—something not feasible within a regular laboratory setting. Many reform efforts are often implemented only once and give neither teachers nor students enough time to apply what they have learned. The living laboratory can provide an approach within a school setting to assess different components of a new effort while maintaining the complexity of the local context.

Theoretical questions about the nature of apprenticeship among children designers in school were a driving force behind this study. On a basic level, this work contributes another crucial and highly detailed case to the small but growing number of in-depth studies of various kinds of formal and informal apprenticeships in the literature on situated learning (Rogoff, 1990). The second aspect of this work in terms of "what we know" about apprenticeship—and the more important feature, we would argue—deals with the quality and possibility of apprenticeship for learning in the educational system. If the model of apprenticeship is to have an influence on research and practice in K–12 education, at a time when innovative, successful models are in demand, more work investigating children's experience is needed.

Researchers such as Brown and Campione (1994) have questioned the extent to which this application of professional practice to student learning is appropriate at all: "[E]ven without an appreciation for daily life in grade school, the armchair philosopher must see the impracticality of suggesting that children be encultured into the society of historians, biologists, mathematicians, and literary critics. This may be the desired state of first-rate graduate school education, but it is surely not a reasonable expectation for grade school. We argue that schools should be communities where students learn to learn" (p. 190). While the learning through design project emulated activities and artifacts of professional software design practice such as the software evaluation visits and use of planning boards, it also was clearly not like a software company in many aspects, such as the need to pay salaries, marketing, etc. Our decisions on how to structure teams, interactions, and classroom activities were based on pedagogical and not economical needs. In this aspect we agree with Brown and Campione. But we also see the benefit of moving beyond a focus on learning skills to aligning learning products and analyses with cultures that are relevant to students—cultures of educational software and of individual classrooms. The construct of apprenticeship can provide a rich and valuable tool for studying learning in schools and among children, if we are willing to give this approach a broader definition.

While many national and state standards have promoted project-based learning approaches, such as learning through design, teachers face significant challenges in implementing them and introducing new cohorts of students each year to project practices. In an analysis of issues on learning how to implement project-based learning, Mintrop noted, "most often, students turned out to be the strongest obstacle of success when they did not behave according to the expectations of the pedagogy" (2001, p. 233). The presence of experienced fifth-graders in our project illustrated how peers can carry out some of the socializing and guiding functions needed to support teachers in the classroom implementation. But the presence of older students alone did not make the difference, as indicated by our observations of the comparison class. It was the presence of experienced older students having participated as fourth-graders in a previous learning through design project *and* having seen modeled more advanced forms of project practices by other fifth-graders.

In addition, the teacher's interactions with students, their teams, and the whole class also facilitated various project practices. As it stands, there are still many open questions that need to be addressed: How does a teacher know when further work with individual students is needed or when team members can take over some of this responsibility? How do teachers decide when to call for whole class sessions and to address project issues that pertain to all and not just some groups? How do classroom teachers balance curricular goals with those of research questions developed by individual students? None of these are trivial questions, and they need to be addressed in teacher practice and professional development to make project-based learning approaches a success.

Finally, the larger issue of any curricular innovation is sustainability to support the continuation of new pedagogies, instructional materials, or new technologies. The mixed grade model of the learning through design approach illustrated how having experienced students, and not just more able students, can make a significant difference in terms of students' individual learning experience and the general classroom activities. More important, such an approach guarantees that there is always a critical number of students in the classroom and in student teams who can introduce inexperienced students to the project activities and team interactions. Our current system assumes that all students master the same content and skills in the same time period, leaving little room to accommodate students with different backgrounds and experiences. The model presented here would provide room to grow over years, not just months, through gradually increasing demands. We realize that the structure of most school organizations is not set up to support such long-term curricular implementations, but this absence alone should not be reason for exclusion. Rather it should force educational theorists and practitioners alike to rethink how we orchestrate schools to provide more developmentally appropriate conditions for learning.

Conclusion

In conclusion, design-based research as a living laboratory offered us the unique opportunity to understand, compare, and evaluate learning through design within the confines of a classroom but beyond the limited perspective of a school year. Neither of our findings alone would have provided us with a thorough understanding of how this project functions and how it can be improved.

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Design-Based Research: More than Formative Assessment? An Account of the Virtual Solar System Project

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Design-based research holds much potential for the field of educational technology. This is especially true for the development of emergent technology for learning where new technology affordances are explored and developed in a principled fashion. This article presents an account of design-based research in action as a way to distinguish between design-based research and more traditional instructional processes. Specifically, the article focuses on the distinction between successive iterations of formative evaluation to improve a particular instructional product and design-based research iterations that focus on the development of more broadly applicable theories, models, and insights vital in the development of emerging technologies for learning.

Introduction

Over the past eight years, we have engaged in a series of related projects to develop the educational potential of the emerging technology of virtual reality. We have tackled the many dimensions of this challenge through a set of design-based methods that have iteratively evolved these projects, our theories, and our methodologies. This article describes the evolution of a particular hardware/software technology developed for use within an intro-level astronomy classroom, but, more than that, it also chronicles the dramatic shifts in thinking related to pedagogical and curriculum structures developed over the course of the study. We argue that this design-based research goes beyond successive iterations of formative evaluation to improve