DIGITAL FABRICATION AS AN INSTRUCTIONAL TECHNOLOGY FOR SUPPORTING UPPER ELEMENTARY AND MIDDLE SCHOOL SCIENCE AND MATHEMATICS EDUCATION

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APPROVAL OF THE DISSERTATION

This dissertation, "Digital Fabrication as an Instructional Technology for Supporting Upper Elementary and Middle School Science and Mathematics Education", has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

Advisor: Glen Bull, Ph.D.

The purpose of this three-paper manuscript dissertation was to study digital fabrication as an instructional technology for supporting elementary and middle school science and mathematics education. Article one analyzed the effects of digital fabrication activities that were designed to contextualize mathematics education at a summer mathematics enrichment program for upper elementary and middle school students. The primary dependent variables studied were the participants' knowledge of mathematics and science content, attitudes towards STEM (science, technology, engineering, and mathematics) and STEM-related careers. Based upon the data collected, three results were presented as having justifiable supporting empirical evidence: (1) The digital fabrication activities, combined with the other mathematics activities at the enrichment program, resulted in non-significant overall gains in students' mathematics test scores and attitudes towards STEM. (2) The digital fabrication activities, combined with the other mathematics activities at the enrichment program, resulted in noteworthy gains on the "Probability & Statistics" questions. (3) Some students who did poorly on the scored paper test on mathematics and science content were nonetheless nominated by their teachers as demonstrating meritorious distinction during the digital fabrication activities (termed "Great Thinkers" by the 5th-grade teachers).

Article two focused on how an instructional technology course featuring digital fabrication activities impacted (1) preservice elementary teachers' efficacy beliefs about teaching science, and (2) their attitudes and understanding of how to include instructional technology and digital fabrication activities into teaching science. The research design

compared two sections of a teaching with technology course featuring digital fabrication activities to another section of the same course that utilized a media cycle framework (Bull & Bell, 2005) that did not feature digital fabrication activities. Based upon analysis of the data collected, two main results were determined to have justifiable supporting empirical evidence: (1) After the instructional technology course featuring digital fabrication activities, the participants reported statistically significant overall gains in science teaching efficacy beliefs. (2) When asked to describe their future plans for using three instructional technologies in their teaching, the top five most mentioned instructional technologies were: interactive whiteboards, video, class website, interactive online timeline, and digital fabrication. Of the participants that mentioned digital fabrication, the specific content areas mentioned were: history (four out of eight students mentioned), social studies (two out of eight), and science, math, engineering, and technology were each mentioned once.

Article three assessed the impact of a series of lessons incorporating a NASA-themed transmedia book featuring digital fabrication activities on 5th-grade students who had been recognized as advanced in mathematics. The main dependent variables studied were the students' knowledge of science content from the Virginia Standards of Learning, attitude towards science, and student reported likes and dislikes about the project. Based upon analysis of the data collected, three main results were presented: (1) Students demonstrated significant positive gains in correct answers to questions on the topic of "Force, Matter, Energy, & Motion" from pretest to posttest. (2) There were nonsignificant gains reported by students on the attitude survey questions about attitude towards science, but this was chiefly because of one question that was significantly impacted in a negative direction. (3) Students articulated five main categories of likes and six main categories of dislikes of the experience, thereby providing insight into their own perception of some of the affordances and constraints of the educational activities. The five topics mentioned most often by students as self-reported likes about the experience included: hands-on activities including building, making, or designing (18 of 29 students mentioned; 62.1%), experimenting (9 of 29; 31.0%), presenting (9 of 29; 31.0%), drawing (6 of 29; 20.7%), and working in groups (6 of 29; 20.7%). The six topics most mentioned by students as self-reported dislikes about the experience included: taking tests (13 of 29 students mentioned; 44.8%), drawing (7 of 29; 24.1%), confusing / too fast (4 of 29; 13.8%), class discussions (4 of 29; 13.8%), reviewing (4 of 29; 13.8%), and attitude surveys (4 of 29; 13.8%).

Cumulatively these three articles aim to contribute to the body of research studying the impact of digital fabrication as an instructional technology for supporting upper elementary and middle school science and mathematics education. This goal is described in greater detail in the "Manuscript Theme" section that begins on the next page.

Keywords: STEM, digital fabrication, upper elementary science education, contextual mathematics, modeling-based science instruction, transmedia books, performance assessment, preservice elementary teacher education, science teaching efficacy beliefs

MANUSCRIPT THEME

The theme for this three-paper manuscript dissertation proposal is an analysis of digital fabrication as an instructional technology for supporting upper elementary and middle school science and mathematics education. There is a national initiative being spearheaded by the federal government to increase development and access to high quality K-12 STEM education (Katehi et al., 2009), and the theme of this manuscript was selected so as to help that effort. This manuscript theme section has four chief parts, the first of which is a discussion of previous research pertaining to the use of digital fabrication as an instructional technology within educational settings, with emphasis upon digital fabrication as an evolving technology. The second part articulates a rationale for why digital fabrication activities should be studied as a mechanism for teaching and learning upper elementary and middle school science, based upon the theoretical framework of modeling-based instruction. The third part articulates a rationale for why digital fabrication activities should be studied as a mechanism for teaching and learning upper elementary and middle school mathematics, based upon the theoretical framework of contextualized mathematics. The fourth part outlines key components of the three papers in this manuscript, and connects those components with the themes articulated in the three preceding parts of this section.

Previous Research on Digital Fabrication as an Instructional Technology

Published empirical research on the use of digital fabrication as an instructional technology within educational contexts is limited in scope. Previous empirical research on the impacts of digital fabrication as an instructional technology has focused upon informal education, formal education, and teacher education, but there is much that is still unknown. This is partially because digital fabrication software and hardware technology are still undergoing the initial stages of diffusion and have not yet achieved mainstream status. As innovative technologies mature and become more robust they can achieve wider dissemination outside of the group of early adopters (Rogers, 2003). Early adopters of digital fabrication as an instructional technology have documented some of the ways in which the designing and manufacturing of physical objects has educational affordances and constraints. As an example, early adopters of digital fabrication as an instructional technology in the field of mathematics education have contended that it has the potential to support students in becoming inventors, creators, and builders (Berry et al., 2010).

So as to determine a robust understanding of the educational affordances and constraints of digital fabrication as an instructional technology within educational contexts, empirical research on digital fabrication should take place within informal, formal, and teacher education. Some of the empirical research on digital fabrication has focused on extracurricular academic programs that had a STEM focus and took place during the summer (e.g., DuCamp, draft; Tillman & Cohen, draft). Studies of digital fabrication as an instructional technology within gifted education have been conducted in the formal upper elementary classroom (e.g., Kjellstrom, draft). Preservice elementary teachers have developed digital fabrication lesson plans that were connected with state standards for mathematics or science (Tillman et al., 2010).

To support the continued efforts in this line of research, the Fab@School Coalition was created. The coalition contains a network of partners, who cumulatively represent education associations (ISTE, AMTE, ASTE, and ITEEA), research universities (UVA, UNT, JMU, and Hofstra), and corporations focused on educational technology (Graphtec, Aspex, and FableVision). The mission of the Fab@School Coalition is supporting the introduction of digital fabrication into education as an instructional technology. Some of the educational contexts pursued by the Fab@School Coalition are informal learning environments, formal classrooms, inservice teachers professional development, and preservice teacher education.

Four topics have been acknowledged by the Fab@School Coalition as paramount in priority if digital fabrication is to become scalable as an instructional technology. The four overriding topics are: (1) development and refinement of curricula, (2) professional development for inservice and preservice teachers, (3) collection and implementation of assessment tools as well as analysis of the data collected, and (4) continued maturation of the hardware and software. Of these topics, this three-paper manuscript focuses upon development and refinement of curricula (i.e., the first and second articles in this dissertation), professional development for inservice and preservice teachers (i.e., the first and third articles in this dissertation), as well as collection and implementation of assessment tools as well as analysis of the data collected (i.e., the first, second, and third articles in this dissertation).

The next two parts of this manuscript theme section articulate a rationale for why digital fabrication activities should be studied as a mechanism for teaching and learning upper elementary and middle school science and mathematics, based upon the respective theoretical frameworks of modeling-based instruction of science and contextualized mathematics. This establishes the framework for the final section in which connections are made to the three specific papers in this manuscript.

Digital Fabrication Supporting Modeling-based Instruction of Science Content

Digital fabrication as an instructional technology might have the potential to support modeling-based instruction (sometimes abbreviated as MBI) of science content. Models sometimes vary in design based upon the user's background knowledge, and high quality models are those that focus a learner's attention on the important properties of the complex phenomena being modeled (Feurzeig & Roberts, 1999). Modeling-based instruction of science emphasizes having students interact with models of complex phenomena. It is not designed to replace traditional or alternative methods of teaching science, but instead the intention is that it be interwoven into a larger science curriculum.

Modeling-based instruction defines a model as a representation of real-world phenomena that has been simplified to focus on key aspects (Buckley et al., 2004). There are many types of models that match this definition, coming from various media: videos, 2D and 3D animations, maps, metaphors, language, and physical objects. What all these different types of models share is the facility to support learners as they develop a deeper and more accurate understanding of what is generally a complex reality (Ainsworth, Prain, & Tytler, 2011).

Modeling-based instruction also varies according to the background knowledge of the user, including both how the models are utilized and the types of models employed (Lohner et al., 2005). Research studies have focused on both discovery-based and semi-open learning environments employing modeling-based instruction for science education (Schwartz et al., 2009). Discovery-based learning environments can provide the students with flexibility in their choices, but sometimes a deficiency of guidance can result in scientific misconceptions and/or inefficiency. Semi-open directed inquiry employing modeling-based instruction of science addresses these concerns by providing scaffolds that focus student attention on aspects of the models that are pedagogically relevant to the science content being taught.

Two key elements characterize modeling-based instruction in science: (1) use of models constructed for or by students, and (2) science activities involving the models (Sengupta & Wilensky, 2009). The nature of the models that students work with, as well as the organization of the learning environment in which they interact with models, can influence their thinking and learning (Lohner et al., 2005). Students often use journaling, discussion, presentations, and artifacts to articulate their understanding of the models (Clement, 2008). This can facilitate teachers' efforts to promote student models that are scientifically accurate (Willensky & Reisman, 2006).

The various student artifacts resulting from modeling-based instruction can also provide teachers and researchers insight into the students' thinking (Lei et al., 2010). Modeling-based instruction sees the student-generated model as a representation meant to communicate key themes, and therefore functioning as a supporting anchor for student-student and teacher-student communication (Penner, 2001). This dialogue can be used to shape correct student understandings of scientific concepts. When combined with the other reasons discussed, this provides a justification for undertaking empirical research on the topic of digital fabrication as an instructional technology for supporting elementary and middle school science education. This part of the manuscript theme section has articulated a rationale for why digital fabrication activities should be studied as a mechanism for supporting modeling-based instruction of science. The next part of the manuscript theme section will articulate a rationale for why digital fabrication activities should be studied as a mechanism for supporting contextualized mathematics instruction.

Digital Fabrication Supporting Contextualized Mathematics Instruction

Digital fabrication as an instructional technology might have the potential to support contextualized mathematics instruction. The importance of learning activities that contextualize mathematics has been recognized by the National Council of Teachers of Mathematics (NCTM) (Williams, 2007). Contextualized mathematics education recognizes that students care about why they should learn how to successfully perform mathematics, not just learning how to succeed at completing math tasks.

An operational definition of contextualized mathematics instruction is "a methodology of teaching that connects academic concepts to real-world conditions and encourages students to see how what they learn relates to their lives" (Williams, 2007; p. 572). In other words, students want to know in what ways mathematics is relevant to their lives outside of the math classroom (Williams, 2007). Contextualized mathematics is one prospective framework for addressing this concern.

The relevance of contextualized mathematics to STEM career preparation has been recognized by the U.S. Department of Education's Office of Innovation in Education. In support of this effort, the U.S. Department of Education funded the Contextual Learning Institute and Consortium (CLIC) project for the primary purpose of examining teachers' and students' perspectives on contextualized mathematics education. The findings from the project report stated that contextual teaching of mathematics requires more planning time and longer class periods, and in return students performed at increased levels of engagement and achievement (Contextual Learning Institute and Consortium, 1997).

Exemplary practices in contextual teaching and learning of mathematics include: (1) encouraging active engagement, (2) encouraging real world experiences, (3) encouraging meaningful learning, and (4) encouraging authentic assessment (Sears & Hersh, 1999). When these four factors are combined, it merits the designation of high-quality contextual mathematics education, within this framework (1999). Sears and Hersh focused predominantly on the ties between mathematical ideas and real-world applications. Other researchers emphasized connections between fluency with mathematical ideas and successfully completing employee responsibilities within various professional positions (Williams, 2007).

Contextualized mathematics instruction can be supported with digital fabrication activities, as for example took place at a summer mathematics enrichment program in 2010 (which served as a pilot study for the first research article in this manuscript). Within this learning environment, students learned mathematical concepts by engaging in digital fabrication activities that contextualized mathematics. Digital fabrication as an instructional technology for supporting contextualized mathematics instruction has just recently begun to be empirically researched. The previous research papers on this topic, many of which are pilot studies, appear to indicate that digital fabrication as an instructional technology might support activities that help contextualize mathematics.

Implementation of the Manuscript Theme Via the Three Research Articles

This final part of the manuscript theme section will outline key components of the three papers in this manuscript, and connect those components with the themes articulated in the three preceding parts of this manuscript theme section. This process is considerate of 'Technological, Pedagogical, and Content Knowledge' (TPACK) wherein technological knowledge is integrated with pedagogical knowledge as well as content knowledge to facilitate high-quality instructional technology integration into an educational setting (Mishra & Koehler, 2006). Three interrelated articles were produced, each applying the TPACK framework in a different instructional technology research context: Article one analyzed the effects of digital fabrication activities that were designed to contextualize mathematics education at a summer mathematics enrichment program for upper elementary and middle school students. Article two focused on how an instructional technology course featuring digital fabrication activities impacted preservice elementary teachers' efficacy beliefs about teaching science, and their attitudes and understanding of how to integrate instructional technology and digital fabrication activities into science teaching. Article three assessed the impact of a series of lessons incorporating a NASA-themed transmedia book featuring digital fabrication activities on 5th-grade students who had been recognized as advanced in mathematics.

Cumulatively these three articles contribute to the body of research studying the impact of digital fabrication as an instructional technology for supporting upper elementary and middle school science and mathematics education, and in particular to the understanding of digital fabrication as an instructional technology that is evolving over time. These three articles are in alignment with the stated priorities of the Fab@School

Coalition, which recognizes (1) development and refinement of curricula, (2) professional development for inservice and preservice teachers, (3) and collection and implementation of assessment tools as well as analysis of the data collected, as three of their top four paramount concerns regarding making digital fabrication scalable as an instructional technology. This three-paper manuscript focused upon development and refinement of curricula (i.e., the first and third articles in this dissertation), professional development for inservice and preservice teachers (i.e., the first and second articles in this dissertation), as well as collection and implementation of assessment tools as well as analysis of the data collected (i.e., the first, second, and third articles in this dissertation).

This manuscript theme section discussed the role of contextual mathematics and modeling-based instruction of science as theoretical frameworks undergirding the use of digital fabrication as an instructional technology in elementary and middle school mathematics and science education. The National Council of Teachers of Mathematics has recognized the negative consequences of only exposing students to mathematics education that does not contextualize mathematics, and that students desire to know how mathematics is applicable to their own lives (Williams, 2007). Contextualized mathematics education is designed to emphasize real-world connections for mathematics, so students understand why mathematics is necessary to succeed in many careers, particularly those in STEM (Sears & Hersch, 1999).

Digital fabrication as an instructional technology supporting contextualized mathematics education in elementary and middle school has only recently begun to be a topic of empirical research, and there is even less empirical research on modeling-based instruction of science content using digital fabrication. This is partially a result of available digital fabrication hardware and software, as of the time of this article, still being in a state of early development and therefore primarily the domain of early adopters (Rogers, 2003). This manuscript theme section has discussed research investigating the potential of digital fabrication as an instructional technology for supporting the teaching and learning of science and mathematics content. The manuscript theme discussion contended, based upon the research cited, that digital fabrication activities might provide a potential mechanism for supporting modeling-based instruction of science and contextualized mathematics instruction.

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Building a Wind Turbine: What are the Affordances of Students using Digital Fabrication within Mathematics Education?

By Daniel A. Tillman and Jonathan D. Cohen

Abstract

This study analyzed the effects of digital fabrication activities that were designed to contextualize mathematics education at a summer mathematics enrichment program for upper elementary and middle school students. The purpose of the study was to determine -the affordances of having students use digital fabrication within a mathematics education context. The primary dependent variables studied were the participants' knowledge of mathematics and science content, attitudes towards STEM (science, technology, engineering, and mathematics) and STEM-related careers. Data collected included mathematics and science pretest and posttest content questions taken from released Virginia Standards of Learning exams, pre-intervention and post-intervention attitudinal surveys on STEM fields and careers, interviews with teachers and students, and student artifacts including digital designs of prototypes and finished prototype artifacts. Based upon the data collected, three results are presented as having justifiable supporting empirical evidence: (1) The digital fabrication activities, combined with the other mathematics activities at the enrichment program, resulted in non-significant overall gains in students' mathematics test scores and attitudes towards STEM. (2) The digital fabrication activities, combined with the other mathematics activities at the enrichment program, resulted in noteworthy gains on the "Probability & Statistics" questions. (3) Some students who did poorly on the scored paper test on mathematics and science content were nonetheless nominated by their teachers as demonstrating meritorious distinction during the digital fabrication activities (termed "Great Thinkers" by the 5th-grade teachers). The article concludes with a discussion of how these results might provide guidance to other similar endeavors that aim to utilize the affordances of digital fabrication within contextual mathematics education.

Keywords: contextual mathematics, digital fabrication, STEM

Introduction

Digital fabrication is the use of student-friendly software and hardware to translate digital designs into physical objects. As an instructional technology digital fabrication has affordances that may benefit elementary mathematics education (Berry et al., 2010). Potential affordances for digital fabrication within mathematics education include increasing elementary teachers' interest and competence in teaching STEM content, as well as increase elementary students' understanding of mathematics in an applied context (Berry et al., 2010). There is a limited body of prior research on digital fabrication as an instructional technology. This is partially because the technology is still undergoing diffusion and has not yet achieved mainstream status.

In order to be productively integrated into elementary mathematics education, the specific affordances as well as constraints of using digital fabrication activities within this setting need to be identified and empirically tested. This study was therefore motivated by the need for empirical research that to investigate potential affordances of digital fabrication in mathematics classrooms, to begin the determination of which scenarios might best utilize this instructional technology.

During the digital fabrication activities, students collected, analyzed, and interpreted data through a project that challenged them to create a real solution to a real problem: developing renewable energy by designing and creating blades for wind turbines. The enrichment program then provided an opportunity to field-test digital fabrication activities that integrated mathematical thinking with scientific experimentation and design.

Within this setting, this study addressed three research questions: (1) What effects do digital fabrication activities that were designed to incorporate mathematics content have upon upper elementary and middle school students' knowledge of mathematics? (2) What effects does engagement in these activities have upon the students' attitudes towards STEM (science, technology, engineering, and mathematics) fields? (3) What are the affordances of having upper elementary and middle school students use digital fabrication within a mathematics education context?

Literature Review

This literature review has two main sections, the first of which will discuss previous research pertaining to the use of digital fabrication within educational settings. The second section will articulate a rationale for why digital fabrication activities should be studied as a mechanism for contextualizing the learning of mathematics.

Previous Digital Fabrication Research

There is very little published empirical research that has been performed on the topic of using digital fabrication within educational contexts. However, several non-empirical scholarly articles have been published on the subject. Bull and Groves (2009) articulated a rationale for how instructional technology can facilitate the designing and manufacturing of physical objects through the process of digital fabrication, allowing students to design and produce media content that spans several formats, from the virtual to the physical. For example, the Fab@Home 3D printer employs a manufacturing method that involves building 3D objects by precisely depositing multiple layers of a viscous material such as plastic or caulk, which then harden into a solid object. User-friendly software is being developed that will simplify and support students in the process of designing such 3D products (Bull & Groves, 2009). The metaphor of "computer-controlled die cutting" (Bull & Groves, p. 36) helps to explain how 2D fabricators can be utilized to design shape-nets that are folded into 3D objects after they have been trimmed and perforated from sheets of heavy cardstock using a digital fabricator such as the Graphtec Silhouette. Such shape-nets can either be printed upon to enhance the designs, extracted from colored cardstock, left uncolored, or written and drawn upon using markers and other colored writing instruments.

Bull and Groves (2009) argued that this suite of fabrication software and hardware technologies can be understood cumulatively as enabling "the democratization of production" (p. 36) and that this process is analogous to the democratization of information that occurred in the 20th century due to the advent of personal computers. Describing the connections and ramifications that this transformation will have upon education, Bull and Groves stated that younger students who have rarely had the opportunity to translate their ideas into replicable physical objects will now have this option via digital fabrication. However, in order for affordances of this opportunity to be maximized within schools and education, such affordances must be recognized and articulated.

One potential domain for the affordances of using digital fabrication with upper elementary and middle students is the integration of engineering design principles and pedagogy into mathematics education. Berry et al. (2010) described some of the preliminary considerations pertaining to the use of digital fabrication as a means for incorporating engineering design principles into elementary mathematics education. One of the primary affordances of digital fabrication is that it can encourage students to be creators, builders, and inventors (Berry et al., 2010) and thereby leverage connections between mathematics and engineering. Previous research on the nature of the diffusion of innovations indicates that as innovative technologies become more mature and robust, they achieve a wider dissemination outside of the group of early adopters (Rogers, 2003). Within this theoretical framework for explicating diffusion, mathematics education that incorporates the innovative technology of digital fabrication by having students engage in the process of creating, building, and inventing, can result in learning activities that have physical contextualization as one of their affordances. The value of such contextualized mathematics is the topic of the next section.

Contextualizing Mathematics

The National Council of Teachers of Mathematics (NCTM) has recognized the importance of activities that contextualize mathematics learning (Williams, 2007). Williams described many of the justifications for this stance in "The What, Why, and How of Contextual Teaching in a Mathematics Classroom". The article described the importance that students place upon not only learning how to successfully complete a mathematical task, but upon also understanding why they should learn how to successfully complete such a mathematical task. Williams argues that students "want to know how mathematics is relevant to their lives" (p. 572) and that one avenue for addressing this need is via contextual teaching, which can help them understand why they are learning mathematics by giving it meaning.

In recognition of the industry and career relevance of contextual learning, the U.S. Department of Education's Office of Innovation in Education funded the Contextual Learning Institute and Consortium (CLIC) project for the purpose of examining students' and teachers' viewpoints on contextualized education. The CLIC project report stated that contextual teaching requires longer class periods and more planning time, but that in return for this investment students performed at increased levels of achievement and were more engaged (Contextual Learning Institute and Consortium, 1997).

Sears and Hersh further articulated the details of exemplary practices in contextual teaching and learning in a summative article (1999) of a National Conference on Teacher Quality that focused on contextual teaching and learning within teacher education programs studies in the U.S. They recognized as exemplary practices those contextualized mathematics efforts that encouraged: (1) active engagement, (2) engagement in real world experiences, (3) engagement in meaningful learning, and (4) engagement in authentic assessment. Within their framework, these four components combined to merit the designation of high-quality contextual teaching and learning. They further described the prevalent strategies for achieving these components as being authentic instruction, inquiry-based learning, problem-based learning, service learning, and work-based learning (1997).

An operational definition of contextual teaching of mathematics that will be utilized for this study is "a methodology of teaching that connects academic concepts to real-world conditions and encourages students to see how what they learn relates to their lives" (Williams, 2007; p. 572). Williams acknowledged that this definition borrows from the earlier work of Sears and Hersh (1999). Sears and Hersh focused predominantly on the ties between mathematical ideas and real-world applications (1999), but Williams also emphasizes the connections between fluency with mathematical ideas and successfully completing the responsibilities that are incurred as an employee within various industry and professional positions.

Contextualizing the learning of mathematics can be supported with digital fabrication, as for example took place at the summer mathematics enrichment program studied: during the morning activities utilizing digital fabrication students participated in contextual learning of mathematics via: (1) recording and analyzing of data collected from real-world activities, and (2) the utilization of digital fabrication to design and manufacture components (i.e., blade assemblies) for small but functional wind turbines that converted energy from kinetic to mechanical to electrical form. Within this environment, students were supported in their efforts to learn mathematical concepts by engaging in activities that involved designing and fabricating material objects in a manner that was intended to facilitate the productive organization of cognitive activity via contextual learning of mathematics.

Digital fabrication as a mechanism for contextualizing mathematics has just begun to be researched empirically, and this study aims to supplement the effort. Digital fabrication activities might provide affordances that contextualize elementary and middle school mathematics, as well as motivate interest and engagement in the STEM fields. The present study seeks to investigate how digital fabrication can offer individualized, authentic learning experiences in mathematics settings for upper elementary and middle school students.

Research Design and Methodology

Overview

Digital fabrication activities piloted at the summer mathematics enrichment program were designed with the intent of enabling an educational environment in which contextualized mathematics learning would take place. Using digital fabrication activities allowed students to engage with a contextualized physical learning environment as they transitioned from: (1) collecting data about physical objects, to (2) designing their own original wind turbine blades, to (3) fabricating physical objects based on their designs, to (4) testing those designs in a series of assessments that culminated in a classroom competition comparing the students' wind turbine blade designs. Digital fabrication thus functioned as a mechanism for contextualizing mathematics in a hands-on, real-world scenario.

The specific context of the study was a summer mathematics enrichment program for upper elementary and middle school students. This two-week program took place in the summer of 2011, and involved 52 fifth- through ninth-grade students. At the time of the study, the summer program was in its third year, having initially been created by the school district for the purposes of: (1) providing a rigorous pre-algebra experience in order to increase the number of students who complete algebra and/or geometry by the

8th-grade, (2) establishing future support including mentoring for participants who completed the program, and (3) improving citizenship.

We used this summer program as a context to field test the use of digital fabrication activities within mathematics education. To facilitate this additional goal, for two hours each morning students engaged in digital fabrication activities that incorporated mathematics and science content. This particular focus involved designing, building, and experimenting with wind turbine blades in order to generate the most power, as measured on a visual voltmeter and a digital multimeter using voltage and milliamps.

The study utilized a convergent parallel mixed-methods design during which both quantitative data as well as qualitative data was collected. Both data sets were analyzed separately, and then their results were combined during interpretation. Quantitative data from students who completed both pretest and posttest mathematics and science content questions were analyzed and used as evidence to answer research question one. Participants in the study also completed a pre-intervention survey and a post-intervention survey that focused upon interest and beliefs pertaining to science, technology, engineering, mathematics, and a career related to STEM. These results were used to address research question two. Qualitative data was collected to address research question number three, including: Interview data collected from students pertaining to the thought process that went into the design of their wind turbine blade assembly prototypes, interview data from some participating teachers regarding their nomination of particular students as excelling at the digital fabrication activities, and physical and virtual student created artifacts were collected and examined.

Setting

As described earlier, the evidence collected for this study was gathered during a summer mathematics enrichment program. This operated within five classrooms at a single school in central Virginia. The students were divided into five classrooms (two of the classrooms were team taught by a pair of teachers) chiefly based upon student grade level. The schedule for parents stated that classes would emulate a full-day academy beginning at 9:00 a.m. and ending daily at 3:00 p.m., from Monday through Friday for two consecutive weeks. During the afternoon mathematics activities students engaged in activities designed to support the stated primary goals of the summer mathematics enrichment program. This entailed provision of a rigorous pre-algebra experience to increase the completion of algebra and/or geometry by the 8th-grade.

Additionally, the program supplied a series of learning experiences designed to improve citizenship, defined as healthy relationships between the students, their families, and the school. Many of the participants in the summer enrichment program were introduced to mentors with whom they would continue to interact throughout the upcoming school year. These mentors were assigned the task of providing their mentees with both individual advice and monitoring, as well as providing guidance and support regarding scholarships, sponsorships, exposure to college, or other relevant academic opportunities.

Participants

This study collected data from a sample of 52 upper elementary and middle school students. Of these students, 13 were rising fifth-graders, 20 were rising sixth-graders, 10 were rising seventh-graders, 7 were rising eighth-graders, and 2 were rising ninth-graders. As noted above, the students were divided into five classrooms, each of which had either a single teacher or a pair of teachers who co-taught. These teachers received occasional observations and feedback from two of the creators of the program; one was a professor of mathematics education, the other was a former school principal.

The 5th-grade classroom was co-taught by a high school mathematics teacher and an upper elementary school teacher. One of the 6th-grade classrooms was taught by a former middle school mathematics teacher (who then transitioned into teaching civics), who also served as a coach for MathCounts, and an elected member of the city school board. The other 6th-grade classroom was co-taught by two middle school mathematics teachers. The 7th-grade classroom was taught by a senior undergraduate student majoring in electrical and computer engineering. The 8th/9th-grade classroom was taught by a retired middle school mathematics teacher. Table 1 below lists the number of teachers, number of students, grade levels and distribution, and teacher background for the five classrooms.

Table 1

Assignment to Classrooms and Teacher Information

Classroom	# of Teachers	# of Students	Grade Level(s) and Distribution	Teacher Background
#1	2	13	Rising 5th	High school math teacher and upper elementary teacher
#2	1	9	Rising 6th	Former middle school math teacher
#3	2	13	Rising 6th (11) & 7th (2)	Two middle school math teachers
#4	1	6	Rising 7th	Senior undergraduate engineering major
#5	1	11	Rising 7th (2), 8th (8) & 9th (2)	Retired middle school math teacher

All participating teachers, except one, received similar professional development. This included an overview of the digital fabrication activities, a demonstration of the digital fabrication activities, and hands-on sessions during which the teachers did portions of the digital fabrication activities themselves. One teacher was unable to attend the pre-program professional development; she received a condensed version of the workshop during the initial days of the mathematics program. In addition to the classroom teachers, each of the five classrooms was assigned an instructional technology assistant, a graduate student with a background in digital fabrication who was responsible for providing technical support for the digital fabrication activities including trouble shooting any difficulties with the digital fabrication hardware and software.

Intervention

The intervention for this study included a sequence of activities distributed over nine sessions (each held for a scheduled 105 minutes) involving digital fabrication activities that incorporated mathematical data collection and analysis, as well as science pertaining to electrical current and power. During the two-week summer camp, students were familiarized with digital fabrication software and hardware, as well as related materials and supports. This enabled them to complete lessons in which they designed and fabricated working wind turbine blades that were attached to a small generator that was then used to generate electricity. Students took multiple readings of real-world data including voltage and amps, which were analyzed using formulas that the students were taught by the teachers with the help of prepared PowerPoint presentations.

The nine sessions of digital fabrication activities that incorporated mathematics and science content began with the first session where students were introduced to energy concepts including kinetic and potential energy, as well as renewable and nonrenewable energy. They were also shown information about wind turbines, including definitions (presented on PowerPoint slides), images, and videos. They then participated in a classroom demonstration of a working tabletop wind turbine which powered an LED light, and was then connected to a multimeter so as to obtain a reading of voltage and milliamps (with a 16-ohm resistor in the circuit) which were then multiplied together to determine the power generated (in milliwatts). The students ended the first session by making initial predictions about what wind turbine blades' variables would influence the amount of milliwatts generated.

The second session of digital fabrication activities began with an introduction to electricity concepts and terms, including: voltage, current, electrical charge, power definitions, and units. Students were also given an overview of scientific notation and electricity related formulas. Students then began constructing and testing prefabricated wind turbine blades prototypes, starting with a blade assembly that included four blades, each of which were three inches long. These were tested at fan speeds of low, medium, and high, and this data describing the amount of voltage and amperage (with a 10 ohm resistor in the circuit) generated at different wind speeds, and with different blade designs, was entered into an Excel spreadsheet. The students then discussed the nature of the data and its precision, as well as made graphs and predictions based upon those graphs. The students also interpreted the data, both locally and globally, and discussed the meaning of the slope of the graph.

The third session began with a summary of the previous two days' activities, and a new round of hypothesis generating and testing. Students then constructed and tested additional predesigned prototypes, including a blade assembly with four blades each of which were four inches long, under the same conditions as the previous day. This data describing the amount of voltage and amperage (with a 10 ohm resistor in the circuit) generated was also entered into a spreadsheet, and graphs of the data were interpreted locally and globally. The students ended this session by comparing the data obtained from the blade assembly with four inch blades to the data obtained from the blade assembly with three inch blades.

Likewise, the fourth session began with further constructing and testing of predesigned prototypes, with the students given the choice of fabricating a blade assembly with either 2.5 or 3.5 inches long blades. This data was interpreted, and then compared to data collected from the previous designs. The fifth session began with a discussion of independent and dependent variables, as well as constants. Students looked at trend lines on their graphs, the slopes of their graphs correlating wind speed with voltage generated for the different blade assemblies, and plotted the data for the different blade assemblies on a single graph. Students then engaged in data interpretation of their graphs, and ended the session with a discussion speculating upon another independent variable that would be tested in upcoming sessions. The second week of the enrichment program began with students constructing and testing blade assembly designs that had varying numbers of blades (predominantly either two, three, or six). Again this data was entered into a spreadsheet and graphed, followed by data interpretation and comparison with voltage generated from the previous week's blade assemblies, which had 4 blades.

The seventh session began with a discussion summarizing previous trials, which was then followed by a demonstration of the visual-voltmeter. The visual-voltmeter displays the volt reading using an array of LEDs, which can be set to represent either one-quarter volt increments (and a maximum of five volts) or set to represent one-half volt increments (and a maximum of ten volts). Once students were familiar with the operation and reading of the visual-voltmeter, they were given an overview of the upcoming contest to design the optimal wind turbine blade assembly, and subsequently began to design and fabricate their own design for entry into the contest.

During the eighth session students also continued to design their own blade assemblies, guided by data collected from the scientific experiments they had conducted the first week. At the ninth session, the students engaged in a contest within each individual classroom, using the visual-voltmeter and a 16-ohm resistor in the circuit. The design criteria for the final wind turbine with blades were that it: (1) Have a base that keeps the wind turbine sitting in one place, and (2) have an assembly that spins from wind power, and thereby turns the shaft on a small generator. The top two designs from each classroom were then eligible to compete against each other in the final contest, which determined 1st, 2nd, and 3rd place overall winners. During the next, and final, day of the program, these top three placers were given the "Awards for Best Wind Turbine Designs" at the celebratory lunch banquet. In addition, each teacher nominated two or three students they felt displayed exemplary behavior during the digital fabrication activities, and these students were honored as well.

Table 2 below lists the sequence of activities including information about the topics and objectives of each session. Other mathematics activities during the afternoon sessions focused upon pattern creation and pattern recognition of numerical and geometric patterns. These activities were all chosen to coincide with the objective of the two-week summer camp -- that the students become better prepared for success in algebra and the more advanced mathematics that follows. The last day of the intervention (10th session) included a ceremony with awards for Best Wind Turbine Designs presented to the top two from each class, and then 1st, 2nd, and 3rd place overall winners.

Table 2

Sequence of Activities Distributed Over Nine Sessions (Each Scheduled for 105 Minutes)

Activity #	Topics and Objectives
#1	Introduction to energy and wind turbines • Kinetic and potential, as well as renewable and nonrenewable • Multimeter demo and student predictions
#2	Intro to electricity concepts and terms • Voltage, current, electrical charge, power definitions and units • Scientific notation and formulas Constructing and testing prefabricated prototypes • 4 blades, 3 inches, at speeds 1,2,3, and discuss precision of data • Enter data in XL (premade), predict and graph, and interpret data
#3	Summary of previous trials • Overview of day 1-2 and hypotheses generating and testing Constructing and testing predesigned prototypes • Fabricate 4 inch blades, run 4 blades, 4 inches, at speeds 1,2,3 • Enter data in XL (premade) and graph, and interpret data
#4	Constructing and testing predesigned prototypes • Fabricate 2.5 or 3.5" blades, run 4 blades, at speeds 1,2,3 • Enter data in XL (premade) and graph • Interpret data: local, global, and slope, and compare to L=2.5
#5	Constructing and testing prototypes • Discuss IV and DV, constants, and trend lines on graphs • Data on all lengths on one graph, and interpretation • Speculate on another IV (such as blade #)
#6	Constructing and testing prototypes (2 inch default) • Fabricate new blades from prototype, adjust length, run 3 or 6 blades, chosen length, at speeds 1,2,3 • Enter data in XL (premade) and graph, and interpret data
#7	Challenge to design best wind turbine • Summary of previous trials, and visual-voltmeter demo
#8	Challenge to design best wind turbine continues
#9	Class contest for most voltage (using visual-voltmeter) • Top two designs from each class compete in final contest

The materials that they were provided to complete this project-based unit included: sheets of 110 lb. cardstock, multi-meters, small electrical motors, medium-sized wind fans, computers with the Fab@School Designer software, Silhouette digital fabricators, and color printers. The students created wind turbine blades built from templates, as well as their own original wind turbine blade designs. The templates assisted them in determining the optimum blade number, length, and angle for maximizing rotations per minute as well as power generated. Through a rapid prototyping process, they refined their final design for wind turbine blades until they felt they had the best wind turbine blades they could make or until time ran out.

Data Collection

Quantitative -- Mathematics and Science Content Pretest and Posttest. The sources of quantitative data collected from students were a mathematics and science content pretest (form A) at the beginning of the summer camp, and a mathematics and science content posttest (form B) at the end of the summer camp. Items were chosen from previous released Virginia Standards of Learning tests, based upon alignment with the mathematics and science content that was embedded in the digital fabrication activities. The Virginia Standards of Learning have tremendous implications for Virginia schools, in that the results are included in the School Performance Report Cards from which accreditation status is determined (U.S. Department of State, 2012).

Selection and matching of items was facilitated and supervised by two mathematics education professors, one specializing in elementary teacher education and one specializing in secondary teacher education. Both forms of the exam contained 20 content questions, of which 12 were from previous Virginia Mathematics Standards of

Learning tests and 8 were from previous Virginia Science Standards of Learning (SOL) tests. Ten of the mathematics questions were from the area of "Patterns, Functions, & Algebra", and, of these, seven were from 6th-grade exams, two were from 7th-grade exams, and one was from an 8th-grade exam. Two of the mathematics questions were from the area of "Probability & Statistics", one of which was from a 6th-grade exam and one of which was from a 7th-grade exam. All of the science questions were from previous Virginia 8th-grade physical science SOL exams. Four of the science questions were from the science area of "Force, Motion, Energy, & Matter", three of the science questions were from "Scientific Investigation", and one of the science questions was from "Earth & Space Systems". Many of the questions (14 out of 20) were paired with a similar, but not identical, SOL question on the pretest and the posttest based upon having a matching topic as well as difficulty level, as determined by the two mathematics education professors. Some of the questions (6 out of 20) were identical on the pretest and the posttest. Please see Appendix A for an example of a paired multiple-choice mathematics question (Figure 1 and 2) and a paired science question from the pretest and posttest (Figure 3 and 4).

Quantitative -- STEM Attitude Survey, Pre- and Post-intervention. Another source of quantitative data for the study was the STEM Semantics Survey (Knezek, Christensen, & Tyler-Wood, 2009). This survey includes a five-part questionnaire that is designed to assess attitude towards the individual fields of mathematics, science, engineering, and technology, as well as a career related to STEM. The survey has 25 questions in total (five questions for each of the particular five topics), each of which utilizes a Likert scale from 1 to 7 to allow the participant to indicate how they feel about the subject. Student participants completed the "STEM Semantic Surveys" once at the beginning of the summer camp, and then again at the end of the summer camp. An example of a section from the STEM Semantics Survey, in this case the mathematics section, is presented in Figure 5 below:

To me, MATH is:

1.	boring	①	②	③	④	⑤	⑥	⑦	interesting
2.	appealing	①	②	③	④	⑤	⑥	⑦	unappealing
3.	fascinating	①	②	③	④	⑤	⑥	⑦	mundane (routine)
4.	exciting	①	②	③	④	⑤	⑥	⑦	unexciting
5.	means nothing	①	②	③	④	⑤	⑥	⑦	means a lot

Figure 5. Example of mathematics section from STEM Semantics Survey.

Tyler-Wood, Knezek, & Christensen (2010) presented validity and reliability evidence for the STEM Semantics Survey which was collected during the spring and summer of 2009. They collected baseline data from a purposely chosen wide range of pertinent convenience samples, including preservice K-12 teachers (n = 58), inservice K-12 teachers (n = 11), upper elementary and middle school students (n = 60), university professors (n = 14), and NSF project evaluators and primary investigators (n = 29). They used the data from these samples to judge the measures for both consistency and relevance, which they equated with reliability and validity respectively. The individual scales on the STEM Semantics Survey were determined to have a Cronbach's alpha ranging from 0.78 to 0.94, and these results were determined to be satisfactory indicators of internal consistency, and therefore reliability. They also assessed the STEM Semantics Survey for content validity, construct validity, and criterion-related validity, and determined that for all areas assessed it met acceptable benchmarks.

Qualitative -- Self-recorded Semi-structured Interviews with Students about their Digital and Physical Wind Turbine Artifacts. Students created reflection videos in which they discussed the final prototype of their wind turbine blade assembly design, providing access to the students' explanation of the design and process by which it was derived. The students' self-recorded reflection videos also provided a demonstration of the wind turbine blade assembly they had created, and the fabricated physical artifacts were collected as well. Digital copies of the students' design prototypes created in Fab@School Designer software were collected in the native file format (.fld). Virtual and physical artifacts are provided as illustrations displaying the qualities discussed during the student generated narratives that they self-recorded in the reflection videos.

Qualitative -- Semi-structured Interviews with Teachers. Teachers in the program were asked to describe the behavior of the students whom they had nominated as excelling at the digital fabrication activities (termed "Great Thinkers" by the 5th-grade teachers). Teachers were also asked to describe the activities that were implemented as they related to students learning probability and statistics content. Interviews with teachers also occasionally focused on determination of: (1) what was perceived as going well during the digital fabrication activities, and (2) what aspects of the activities were causing concerns (such as behavioral problems impacting classroom management, or technical problems involving digital fabrication hardware and software). These interviews were used to expose and troubleshoot issues occurring in the classrooms that needed immediate attention, as well as to inform the research question of the affordances of digital fabrication activities as a mechanism for contextualizing mathematics education.

Data Analysis

Quantitative -- Mathematics and Science Content Pretest and Posttest. Quantitative data collected from the pretest and posttest were analyzed to determine mean pretest score correct and mean posttest score correct; these averages were then used to calculate percentage change as well as standard deviation for each participant. All questions on the pretest and posttest were weighted equally and assigned a value of 1 point if correct, and 0 points if incorrect. These scores were then combined into an overall composite, both for the entirety of the participants as well as separated by grade levels. A dependent (paired) samples t-test, with an assumed p-value of 0.05 and two-tails, was then used to determine if any of the findings represented statistically significant results. Total numbers of pretest correct and total numbers of posttest correct were also calculated for the individual questions, and then these overall composite scores were then used to determine the percentage change. The individual mathematics and science questions were then combined by areas, such as for example "Patterns, Functions, & Algebra" within mathematics, and average percentage change was then calculated for all questions within that area. This resulted in a determination of the overall average percentage change for the two mathematics areas as well as the three science areas that were assessed.

Quantitative -- STEM Attitude Survey, Pre- and Post-intervention. Quantitative data collected from the STEM Semantics Survey was analyzed to obtain an assessment of participants' self-reported interest and engagement with math, science, engineering, and a career related to STEM. Scores were measured both before completing the summer camp curriculum and after completing the summer camp curriculum, using the instrument's Likert scale wherein 1 is the lowest score and denotes no interest and 7 is the highest score, denoting extreme interest. (Some questions used the reverse scale, but these scores were flipped prior to data analysis). Mean scores and standard deviations were calculated for both the pre-intervention and post-intervention survey data, as well as the percentage change. Dependent (paired) samples t-tests using a two-tailed test with a p-value set to 0.05 were then analyzed to determine whether there were statistically significant differences between the pre-intervention and post-intervention scores. Results from the STEM Semantics Survey were also analyzed to determine overall average attitude towards mathematics among the different grade levels. This entailed calculating, for each grade level, the pretest mean and standard deviation, posttest mean and standard deviation, and percentage change between the pretest and posttest mean. Additionally, t-test scores were calculated using the same assumptions as for the individual subject areas.

Qualitative -- Self-recorded Semi-structured Interviews with Students about their Digital and Physical Wind Turbine Artifacts. All students were asked to create self-recorded reflection videos in which they demonstrated and discussed their wind turbine blade assembly digital design and final physical prototype, and transcriptions of these videos were used to supplement interpretation of the quantitative findings (the 5th-grade students did not participate in creating self-recorded reflection videos). As a visual illustration to complement the transcriptions of the interviews, where appropriate, images from the students' self-recorded reflection videos demonstrating their final design prototypes are also presented (with the students' faces blocked). These illustrations from the self-recorded reflection videos are reinforced with screenshots of the students' design prototype as it was created within the Fab@School Designer software. The aim of this analysis was to use the student-created reflection videos, in which they discussed the final prototype of their wind turbine blade assembly design, as a means of offering access to the students' explanation of the design and process by which it was derived. The students' self-recorded reflection videos also provided a visual demonstration of the wind turbine blade assembly they had created (and the fabricated physical artifacts were collected as well). Digital copies of the students' design prototypes created in Fab@School Designer software were collected in the native file format (.fld). Screenshots of these designs are presented as illustrative figures in the results section of this paper.

Qualitative -- Semi-structured Interviews with Teachers. Transcriptions of the interviews obtained from the teachers were used, where appropriate, to support or refute evidence obtained from the mathematics and science content pretest and posttest, as well as the attitudinal data obtained from the STEM Semantics Survey. Interview responses were also analyzed to address the research question of the affordances of digital fabrication outside of possible impacts upon mathematics or science content knowledge, or attitude towards STEM. The interviewed teachers were asked to describe the behavior of the students whom they had nominated as excelling at the digital fabrication activities (termed "Great Thinkers" by the 5th-grade teachers) and these data were used to contribute to student performance on quantitative measures.

Results

The research design for this study emphasized data collection and analysis intended to provide sufficient evidentiary warrant for positing justifiable results that addressed the research questions. Three findings with supporting evidence were obtained from piloting the digital fabrication activities with the students and teachers who took part in the mathematics enrichment program.

Result 1: The digital fabrication activities, combined with the other mathematics activities at the enrichment program, resulted in non-significant overall gains in students' mathematics test scores, science test scores, and attitudes towards STEM. Comparing the students' pretest and posttest answers showed that mathematics scores went up an average of 13% among the 52 students participating in the study. These results were not statistically significant. Table 3 below describes the overall results from the mathematics content questions.

Table 3

Results from Twelve Mathematics Questions on Pretest and Posttest (n = 52)

Pretest correct	Posttest correct	Stan. dev. (pretest)	Stan. dev. (posttest)	% change	Dependent t-test
6.9	7.8	2.69	3.07	13%	0.11

Given the mixed-methods design of this study, these quantitative data are enhanced by interviews with the teachers. One of the 6th-grade teachers stated:

> With the actual turbine activities, there was more of an emphasis on the science concepts than with the math involved. Once students knew that they were being judged on voltage and amps, they turned their efforts toward tweaking the variables to come up with an

> efficient design. The design analysis of the blades played a big role in where they chose to focus their attention.

This comment would suggest a greater increase in science scores than math. However, overall science scores declined an average of -9%. None of these results was statistically significant. Science scores went down for each individual grade level with the exception of the 10th-graders who went up 8%. Table 4 below describes the overall results from the science content questions. It is believed that some of the explanation for this result is that the SOL test questions used did not align strongly enough with any knowledge gained in science via the activities.

Table 4

Results from Eight Science Questions on Pretest and Posttest (n = 52)

Pretest correct	Posttest correct	Pretest stan. dev.	Posttest stan. dev.	% change	Dependent t-test
4.8	4.4	1.58	1.56	-9%	0.17

Average percentage change in each of the three science areas tested, which included "Force, Motion, Energy, & Matter", "Scientific Investigation", and "Earth & Space Systems", was negative. None of these results was statistically significant. Again, teachers' comments speak to some of the factors for these results. One of the teachers said:

> Since most of us were math teachers, I think there was some anxiety about teaching science, as it was not our content specialty. I think the professional development done previous to the [summer mathematics

> enrichment program] didn't allow for us to really investigate what we were teaching the students. To some degree the professional development was rushed and teachers didn't ask questions because I don't believe we really knew what questions to ask. It would have been helpful as a group to collectively work through the process from the beginning to the end with the windmills, and maybe even had some opportunities to touch base after teaching to address concerns.

Another teacher echoed this sentiment, stating:

> I was not greatly familiar with the science (electricity and physics) behind this project. I felt I wasn't able to advise them as effectively had I had a greater command of the concepts.

Regarding student attitudes towards mathematics, science, engineering, and technology, as well as a STEM related career, these were non-significant gains. The student participants self-reported an average 4% increased positive attitude towards science, mathematics, engineering, technology, and a career in STEM, with the largest increase in positive attitude towards engineering, with a 9% increase. None of these results was statistically significant. Table 5 below reports the percentage change for the student participants, separated by subject area as well as the overall combined results.

Table 5

Results from STEM Semantics Survey Separated by Subject Area and Overall (n = 52)

Subject area	Pretest mean	Posttest mean	Sta. dev. (pretest)	Sta. dev. (posttest)	% change	Dependent t-test
Science	25.4	26.2	8.40	8.36	3%	0.23
Math	28.2	29.4	6.78	5.83	4%	0.17
Engineering	25.2	27.5	8.54	7.36	9%	0.06
Technology	28.4	29.1	6.49	5.5	2%	0.49
STEM Career	28.6	29.3	7.77	5.89	2%	0.56
Overall STEM	135.8	141.4	27.12	23.55	4%	0.26

One of the 6th-grade teachers described why she believed there were no statistically significant results regarding attitude towards individual STEM subject areas or STEM overall:

> I wonder how the two weeks would have gone were the students to construct the blades themselves [at the beginning of the activities] rather than using the initial templates. I feel the greatest take-away for the students was obtaining and/or strengthening their ability to apply a trial/error process. Before throwing out a design that "didn't work," I asked students to look for slight (square inch out of proportion) or more obvious (only 2 of the 4 blades with a fold) variations. It was common to see a separate group [of students] offer assistance in order to figure out any weaknesses in a blade design.

Result 2: The digital fabrication activities, combined with the other mathematics activities at the enrichment program, resulted in noteworthy gains on the "Probability & Statistics" questions. "Probability & Statistics" was the mathematics area with the highest overall gains, with an average of 45% improvement in number of questions answered correctly. One of the teachers of the 5th-grade students spoke specifically to the interplay of morning (digital fabrication) and afternoon (math) activities in facilitating this outcome:

> The kids were organized in small teams, so we had a lot of support in terms of that. So there was a big emphasis upon mean, median, mode, range. [One of the 5th-grade teachers] emphasized that, especially in the afternoon when they did just math. And then there was a huge application of that information in the morning with the wind turbine activities. Like the kids, the kids would sit there and I would -- they were actively applying the skill of finding averages. They were like [saying to each other] 'okay, now we have to find the average' like they were running on their own. There was a couple of days of supporting that, and then the kids naturally got the knack of taking the measurements and finding the averages and they were doing it accurately. There were group discussions in front of the whiteboard. ... Especially [one of the 5th-grade teachers] had the whole class together at the front of the room and would review the content.

The teacher later provided a specific example:

> Like they knew if the moved the fan or if they changed the speed of the fan that it was going to impact the outcomes and they knew that they couldn't do all of it at once. So they were aware of like the controlling of the variables. I don't know if they necessarily knew why but they kind of got it, like [the students were saying to each other] 'well like that will mess up the information don't do that yet'. Or like when the blades were having issues they totally picked up on that [saying to each other] 'this is not right, something is wrong here'. So they'd go back and reevaluate the situation.

The teacher also spoke to the students' problem solving efforts:

> There was a lot of problem solving going on, multiple measurements going on for everything, good discussion. There were discussions about discrepancy, like why did this group get such different numbers then this group, and what are the possible causes.

Comparing the posttest scores from the rising 5th-graders at the summer enrichment program on the "Probability & Statistics" questions with Virginia 7th-grade students who actually took the SOL test shows that the rising 5th-graders, following the summer enrichment program, scored higher (with 84.6% correct) on question #6 than did the actual 7th-graders (with 75.4% correct). On "Probability & Statistics" question #6, the thirteen rising 5th-graders went from 3 students answering correctly on the pretest to 11 answering correctly on the posttest, for a percentage change of 267%. On "Probability & Statistics" question #3, the thirteen rising 5th-graders went from 2 students answering correctly on the pretest to 9 answering correctly on the posttest, for a percentage change of 350%.

The illustrations below (Figure 6 and Figure 7) show Question #3 from the pretest and posttest that were similar matched questions, defined as having a similar topic as well as difficulty level on the pretest and posttest question as determined by two mathematics education professors. On the pretest 31 of the 52 (60%) students answered the question correctly, and on the posttest 42 of the 52 (81%) students got this question correct.

Cheeseburgers Sold
Last Week

Day	Number
Sunday	59
Monday	34
Tuesday	38
Wednesday	44
Thursday	46
Friday	87
Saturday	92

What is the range of the data?

F 33
G 44
H 58
J 92

Figure 6. Question number 3 on the pretest.

Travel Time to School

Student	Time (in minutes)
Jennifer	14
Randy	10
Kris	6
Jordan	18
Tia	13
Sam	10
Josh	9
Simon	15
Ray	10

What is the range for the times listed in the table?

A 4 min
B 9 min
C 10 min
D 12 min

Figure 7. Question number 3 on the posttest.

Figure 8 below shows Question #6, which appeared both on the pretest and the posttest, and showed an overall average increase of 54% correct for all participants from the pretest to the posttest.

High Temperatures for Oakwood City

Day	Temperature (°F)
Mon.	56
Tue.	59
Wed.	62
Thu.	62
Fri.	61
Sat.	62
Sun.	59

Which is closest to the mean (average) high temperature?

A 56°F
B 60°F
C 61°F
D 62°F

Figure 8. Question number 6 (on both the pretest and the posttest).

In this question, students were asked to determine the "mean (average) high temperature" based upon the data table presented. On the pretest 26 students answered correctly, on the posttest 40 did so. The average gains for all participants from the two "Probability & Statistics" questions are described in Table 6 below:

Table 6

Results from the Two "Probability & Statistics" Mathematics Questions (n = 52)

Question #	SOL grade	Pretest correct	Posttest correct	% change
3	6	31	42	35%
6	7	26	40	54%

Result 3: Some students who did poorly on the quantitative mathematics and science assessments were nonetheless nominated by their teachers as demonstrating meritorious distinction during the digital fabrication activities (termed "Great Thinkers" by the 5th-grade teachers). Towards the end of the mathematics enrichment program, the students held a competition to compare the wind turbine blade assembly designs they had created (measured by volts generated with a 16 ohm resistor in the circuit). Among the designers of the three top wind turbine blades in the contest, only the second place winner had positive gains on the percent change from pretest correct to posttest correct, while the third place winner had no gains on the percent change from pretest correct to posttest correct, and the first place winner had a 25% decrease from pretest correct to posttest correct. The first place winner (see his scores in Table 7 below) was a rising 6th-grader

(competing against 7th, 8th, and 9th graders) who did not fit the conventional mold of a stellar student, yet he excelled within this type of learning environment, and created a wind turbine blade that ultimately produced 4.0 volts at the final camp contest.

Table 7

Results from the Top Placer in the All-Classes Wind Turbine Blades Contest

Pretest correct	Posttest correct	% change	Math pretest	Math posttest	Math change	Science pretest	Science posttest	Science change
8	6	-25%	6	2	-67%	2	4	100%

This student's teacher described him during her interview:

> This was the second year that I had the opportunity of working with [him]. In year two, he still impressed me as a bright, excited, and engaging student. He clearly enjoyed working on the various assignments and liked problem-solving to reach the targeted goals. As with the time I got to know him during the summer of 2010, [he] exhibited behaviors that I did not find conducive to achieving full success. While ultimately he would finish tasks, it took a lot of teacher encouragement to get him to both stay on task and provide alternate solutions to challenges instead of giving up. He still had an argumentative streak that came out even with simple all-class teacher requests (e.g., getting out notebook, doing prep work (i.e., pre-read) before engaging in hands-on portion, cleaning up work area). During the second summer of working with [him], it was noticeable to me that the

frequency, intensity, and duration of his argumentative bouts was diminished as compared to the previous summer. I pointed this out to him, and shared that he would continue moving toward more positive ways of interacting with teachers and peers.

In his self-recorded video, this fifth grade student described his design:

> This is my blade design, the first time I had it made it just, these two, this one and this one [pointing at supports on two of the three blades on the assembly], but I had to make all these [pointing at additional supports on the blade assembly] because it wasn't stable, it was kind of floppy. But now it's not floppy as you can see. It was hard it was, to find the design, but it went fast compared to my other ones. And it's awesome. I like it. It's a Y (description of shape, see Figure 10). Mine is stable and I like it a lot. And my first one, it didn't have enough grip, I think cause -- this was my first one -- it didn't have enough grip in the middle [pointing to center of blade assembly] it was too big, I didn't make it [the center of blade assembly] an inch but this one [displaying earlier model with larger center hole] I taped it and it messed up but it still went fast. But I'm doing -- I did another one and it's going to go really fast.

The diagrams below, Figure 9 and Figure 10, illustrate what the student meant by the wind turbine blade assembly being a Y-shape. This three-blade, or Y-shaped, assembly is similar in blade number and blade spacing to many of the professional wind turbine blade assemblies available in the commercial market that also use an evenly spaced three-blade design. Having a student generate a 3-

blade design similar in blade number and spacing to commercial models, and having that design as the eventual winner of the student contest, provides evidence for the authenticity of the contextualized mathematics activities in which the students participated.

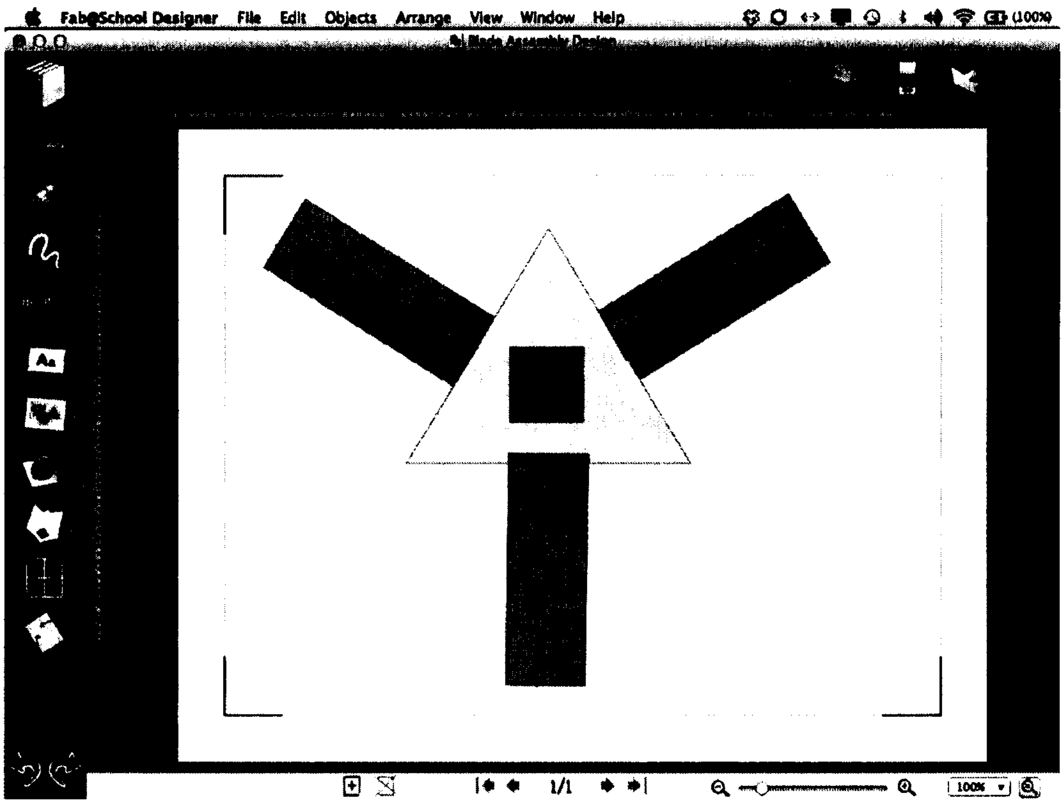

Figure 9. Winning turbine assembly design created in Fab@School Designer.

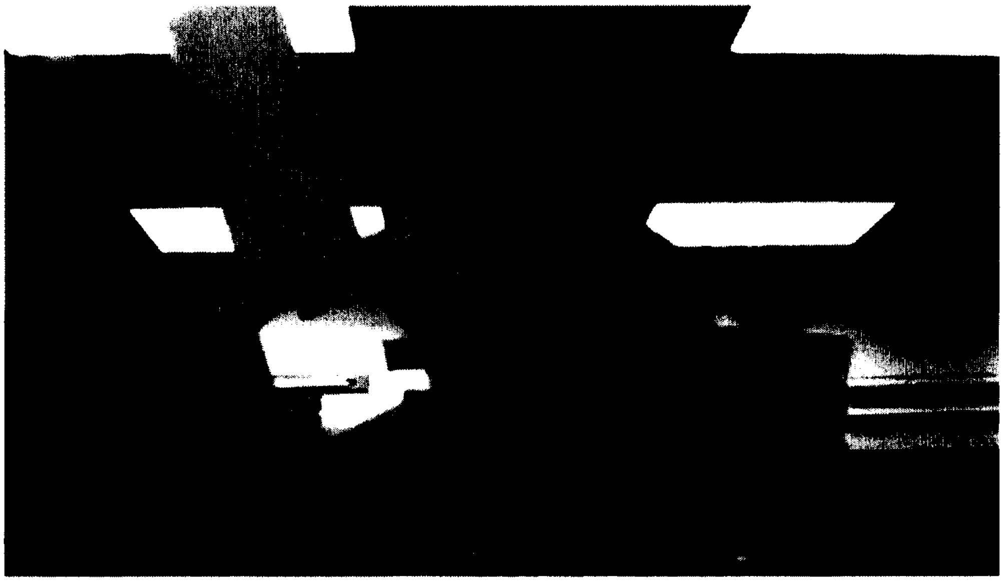

Figure 10. Still image from a self-recorded video made by the designer of the winning turbine assembly displaying the design prototype which produced 4.0 volts.

In addition to the contest to determine the top three student designs for wind turbine blades, individual teachers were asked to each nominate two or three students (termed "Great Thinkers" by the 5th-grade teachers) that they felt should receive recognition as demonstrating outstanding performance during the duration of the digital fabrication activities. Some of these nominated students quantitative results decreased on the pretest to posttest percentage change, including a 5th-grader who decreased by -45%, a 6th-grader who decreased by -54%, and another 6th-grader who decreased -20%. Table 8 below describes the full scores and percentage changes for these three students.

Table 8

Results from 3 Students Nominated as "Great Thinkers" for the Wind Turbine Activities

Grade level	Pretest correct	Posttest correct	% change	Math pretest	Math posttest	Math change	Science pretest	Science posttest	Science change
5th	11	6	-45%	6	3	-50%	5	3	-40%
6th	13	6	-54%	7	3	-57%	6	3	-50%
6th	10	8	-20%	6	6	0%	4	2	-50%

Here again, the teacher interviews addressed the discrepancy in performance and teacher assessment. The 5th-grade "Great Thinker's" teacher described him:

> [He] was quiet and shy yet thrived when asked or assuming any kind of leadership role in a group. He often struggled with students who were unable to think first and then share ideas. He definitely needed that think time to process and determine how he was going to move forward solving a problem, building or constructing with the turbine, etc. [He] didn't like to struggle and would often times shut down when he became frustrated with a task or assignment. [He] also worked best with students who thought as critically as he did and pushed his ability to think.

The "think time to process and determine how he was going to move forward solving a problem" appears here to have been facilitated by the digital fabrication activities, which allowed for an extended period of time to grapple with a complex design problem. Likewise, the two teacher-nominated 6th-grade "Great Thinkers" were in a group together, and described their design in their self-recorded video.

> So we came up with our blade, the design for our blade, cause we've been thinking about Scary Movie 2 [movie title] and so we wanted to make it all like crazy and weird, freaky like Scary Movie 2, yeah like Scary Movie 2. So what worked well was the sticks [used as a support material to keep the blades from bending], they kept it stable and made it move a whole lot faster then all the other people. Yeah, so what worked well with our group was we always laughed a lot and played and stuff but we still got our work done. We mostly played and laughed, but still we got our work done. So yeah, and we mostly we were thinking about Scary Movie 2.

Again, the students echo the notion of a complex design problem solved over an extended period of time, but in this solution they use a metaphor borrowed from an impactful (upon them) cinema experience they had had earlier in the summer. The application of a "Scary Movie" theme to their design solution, aiming for a wind turbine blade assembly that was "all like crazy and weird, freaky" again resulted in them enaging in contextualized mathematics via digital fabriation activities wherein the students, in the words of the 5th-grade teacher, had "think time to process and determine how ... to move forward solving a problem". The illustration below, Figure 11 and Figure 12, elucidate what the student meant by a "scary movie" theme, with the end result being a six-blade wind turbine assembly, where each of the blades ends in a sharp point. That these students constructed a working blade assembly based around their chosen metaphorical theme provides evidence for the engagement levels that they achieved while partaking in the contextualized mathematics activities of designing and fabricating their final prototype.

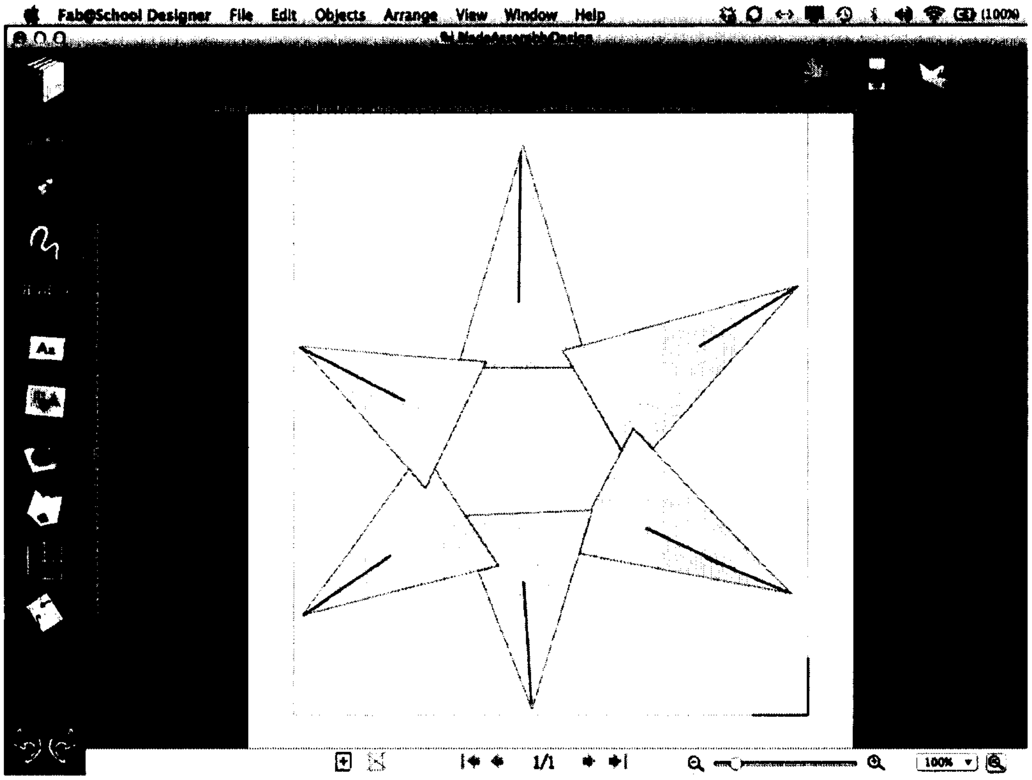

Figure 11. Turbine assembly design with sharp pointed blades and a "scary movie" theme, created in Fab@School Designer by group including two 6th-grade students nominated as "Great Thinkers".

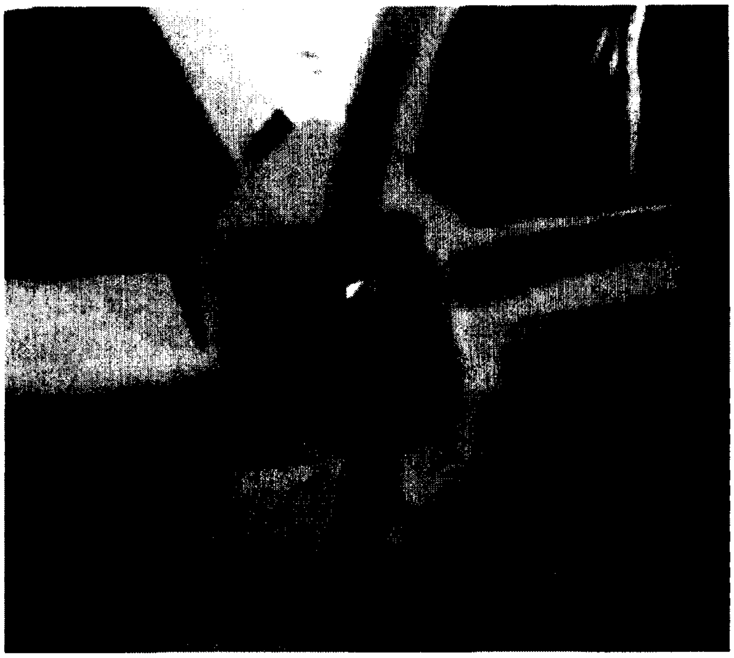

Figure 12. "Great Thinkers" nominees, and creators of a "scary movie" themed turbine assembly displaying the design prototype in a self-recorded video.

These digital designs and fabricated prototypes provide artifacts that demonstrate students participating in the type of problem-solving that Roth (1996; p. 163) described as a central component of contextual learning, stating: "the construction of artifacts is far more important to learning than simply to motivate students. Materials, tools, and artifacts serve in important ways as structuring resources to design and make sense of the learning environment and as backdrop against and with which students can construct individual understandings and negotiate shared meanings. Design activities in which students collectively construct artifacts should thus become central aspects of learning rather than appendixes with mere motivational purpose."

Discussion

In this discussion section, the three results and supporting data presented in the previous results section are examined (1) both as regards to how they address the research questions, and as to (2) how they might provide guidance to other similar research or practitioner-oriented endeavors.

Result 1 -- Outcomes from Mathematics and Science Content, and STEM Attitude

Students' overall math performance pretest to posttest did not improve significantly. Possible explanations for the student outcomes regarding mathematics content pretest and posttest questions described in the first result are that: (1) the digital fabrication activities did not provide students sufficient experiences with essential mathematics content that was measured with the pretest and posttest questions, (2) there was insufficient professional development for the teachers on the topic of how to implement the digital fabrication activities that were designed to contextualize mathematics, (3) some of the students might have spent a considerable portion of their educational time and resources focusing on the aesthetic choices involved in the design process such as choosing the color pattern printed on the wind turbine blades, and (4) perhaps some of the students did not take the posttest exam seriously. Another complicating factor was that the teachers were for the most part selected based on their experience with teaching mathematics in a traditional manner, not teaching contextual mathematics using hands-on activities, and this might have compounded the problem.

Students' science performance pretest to posttest also did not improve significantly. Possible explanations for the student outcomes regarding science content pretest and posttest questions described are that: (1) the digital fabrication activities did not provide students sufficient experiences with essential science content because teaching science content was not a foremost purpose of the program, (2) there was insufficient science pedagogical content knowledge professional development for those teachers that lacked a background in science, and (3) some of the students did not take the posttest exam seriously. Further, the teachers were for the most part selected based on their experience with mathematics, not science, and this might have compounded the problem.

An additional complicating factor, insufficient amount of time-on-task, might have contributed to some students obtaining negative or zero gains in pretest versus posttest scores. Content that was determined to be essential to the lessons should have been emphasized on multiple occasions, as well as have had central placement in the curriculum. That this did not occur may have been the result of the insufficient professional development for teachers. Classroom instruction, as well as the instructional design that moderated it, sometimes resulted in essential content receiving tangential treatment. This perhaps resulted in students obtaining non-significant gains in pretest versus posttest scores on science questions. As an illustration, Figure 13 below shows question number 14 (on both the pretest and the posttest) was:

Consumers of electrical energy are billed according to how much energy they use. The unit most commonly used for measuring electrical energy consumption is the —

F millivolt
G ohmmeter
H newton-meter
J kilowatt-hour

Figure 13. Question number 14 (on both the pretest and the posttest).

The number of students who answered this question correctly dropped -17% from the pretest to the posttest. Perhaps this was because the content was given tangential treatment, in that while students were required to calculate watts using a multimeter and a spreadsheet (by obtaining separate measurements for volts and milliamps, and then multiplying the two), they were also using a visual-voltmeter (displaying volts using a series of illuminated LEDs) that had popular appeal because of availability, readability and entertainment value. The engagement with the visual-voltmeter might have contributed to some students gaining the misconception that electrical energy consumption is measured in volts instead of watts. This question thereby illustrates the importance of designing instruction that allows multiple experiences with essential content while matching the language of instruction to the language of the test. The students had perhaps increased their knowledge but could not find in the question the new familiar terms they had learned.

Teachers who lacked a background in science might have benefited from receiving additional professional development in science pedagogy, as well as science content. In future implementations of similar activities, teachers could benefit from receiving additional professional development in the science content and science pedagogy relevant to the specific activities if they are going to be expected to teach that science content effectively.

Regarding results from the survey on self-reported attitude towards the STEM fields, the overall percentage changes were all non-significant. It is possible that digital fabrication activities that contextualize mathematics education might influence students' attitudes towards these subject areas if there is more time devoted to the activities, but perhaps the limited time, a two-week summer enrichment program, did not provide sufficient exposure to impact these measures.

Result 2 -- Results from "Probability & Statistics" Questions.

Although in general math results pretest to posttest did not reveal significant gains, the results from the "Probability & Statistics" questions described in the previous section -- including overall average percent change of 45% increase from pretest to posttest -- provide some evidence that in combination with the afternoon math activities the morning digital fabrication activities provided a mechanism for supporting the teaching and learning of contextual mathematics education. As the students repeatedly collected, analyzed, and interpreted data they engaged with the social and physical environment, and the construction of physical artifacts. These artifacts enabled them to collect multiple readings of data that they then analyzed for attributes such as spread (younger students), range (older students), and average (all students).

This increase in average percent change of 45% from pretest to posttest on the "Probability & Statistics" questions might be explained by the combination of the afternoon math activities with the morning digital fabrication activities, during which students collected multiple readings from the digital multimeter and the visual-voltmeter. They then entered this data into a spreadsheet, and calculated the mean value. This data was then used in comparative experiments of the different wind turbine blade assemblies, as well as the subsequent refinements of their own blade assembly designs, thereby engaging the students in contextualized mathematics.

Reinforcement for the type of problem-solving required by this question occured in the afternoon sessions, during which students sometimes engaged in spreadsheet activities involving manipulatives; these often focused on data collection, data analysis, and data interpretation, and included calculating averages and ranges. The digital fabrication activities involved several facets, and a repeated theme was taking multiple readings of data and then analyzing the average and the range (for younger students it was sometimes the spread instead of range). Future research may be be able to assess the contribution of each component. Separating the impact due to the digital fabrication activities from the impact due to the afternoon mathematics activities is not possible; perhaps it was the combination of both that resulted in the impact described.

Result 3 -- Teacher-Nominated Meritorious ("Great Thinkers") Performers

The third result provides evidence that the type of hands on experiences provided by the digital fabrication activities appears to be of value to some students who don't necessarily demonstrate meritorious distinction on more traditional assessment methods such as multiple-choice tests. These results thus provide empirical evidence that digital fabrication activities that contextualize mathematics education, such as those that were utilized at the summer mathematics enrichment program, may serve as an engaging opportunity that might impact students' engagement with mathematics and science content despite not necessarily resulting in statistically significant increases on traditional mathematics and science content multiple-choice tests. The teacher nominations thereby provide additional measures that support the notion that student engagement is important in pilot efforts such as this one, and suggest that performance measures, such as success on tasks, may portray a different picture of students than paper-pencil tests.

Limitations

Affordances and obstacles of digital fabrication activities that aim to contextualize mathematics have been partially revealed by this study. There were several limitations of the study that adversely impacted the outcomes obtained. The most notable of these limitations are: (1) It is plausible, as mentioned earlier, that the SOL questions administered during the pretest and posttest lacked sufficient alignment, in terms of content or vocabulary used, with the mathematics and science that the students learned during the summer enrichment program, and that this negatively impacted the results obtained. (2) A two-week intervention may be insufficient time for noticeably influencing students' self-reported changes in attitude and engagement with mathematics and science content. (3) The intervention might have lacked sufficient professional development for the participating teachers, particularly as regards the science pedagogical and content knowledge necessary to lead the digital fabrication activities. (4) The afternoon pre-algebra activities involving patterns and functions and the morning digital fabrication activities both contained content relevant to some of the pretest/posttest content questions, and it was the combination that resulted in the impact described. (5) The timing of the administration of the posttest in the second week of the intervention might have negatively impacted the students' efforts to exert a full effort on the test questions.

Nonetheless, field-testing the wind turbine blades design activities in the informal learning environment provided by the summer mathematics enrichment program did allow an assessment of their impact as a mechanism for teaching and learning contextual mathematics education. The pretest and posttest mathematics questions that we thought would assess content knowledge acquired by the students led to non-significant results. However, some of the questions did reveal noteworthy gains namely those on the topic of "Probability & Statistics"; perhaps this was because they were addressing content repeated in the morning and afternoon sessions, but perhaps it was also because the contextualization of the mathematics involved increased the students' engagement with the activities by providing an answer to the question of how mathematics can be relevant to real-world problem solving. Although non-significant, the students' increases in mathematics content knowledge and attitude towards mathematics are an indicator of the potential value in continuing to advance the development of digital fabrication activities that are designed to help students learn contextualized mathematics.

Plans for future research, described in the next section, aim to continue within the line of inquiry presented in this study, and will strive to address these limitations so as to minimize their influence. Future research will focus on extricating an understanding of the impact of the digital fabrication activities if they are not in combination with other mathematics activities, or subject to the other research design limitations articulated in this section. It is believed that this continued effort is warranted in that providing an educational context in which students with different types of skills and aptitudes can demonstrate success and develop confidence might provide a portion of the justification for why digital fabrication activities that contextualize mathematics education should be further researched.

Future Research

This pilot study was intended as a launching point for further studies on the impacts of digital fabrication, and was undertaken with the objectives of detailing affordances as well as obstacles and difficulties that arise in this context, and that will need to be addressed if similar interventions are to become scalable. The study aimed to provide useful information to: (1) researchers addressing the pedagogical affordances and constraints of implementing contextualized mathematics education using digital fabrication activities, (2) preservice and inservice teachers considering or actively implementing related mathematics or STEM activities in the classroom and informal settings, and (3) instructional designers and curriculum developers involved in the design and development of similar mathematics or STEM activities. There is much to learn about the pedagogical and logistical aspects of implementing contextual mathematics education utilizing digital fabrication activities, and this study had the purpose of contributing to elucidation of research questions relevant to this objective.

A continuation study involving a more prolonged exposure to a similar intervention is therefore currently (fall 2011 and spring 2012) being undertaken with a group of 36 5th-grade students identified as advanced in mathematics, and data collection is expected to complete by March of 2012. The findings from this continuation study are predicted to provide empirical evidence that digital fabrication activities might have the potential to influence student attitudes towards the STEM areas if the duration of the intervention is increased. Although the current study measured non-significant impacts on the participants' self-reported attitudes toward the STEM fields, the continuation study is warranted in that the National Science Foundation has identified student attitudes towards science, mathematics, engineering, technology, and a career in STEM as key components to our success in developing a competitive 21st-century workforce.

Another study continuing this line of inquiry is currently being undertaken (fall 2011 and spring 2012) with preservice elementary teachers as the participants, and data collection is expected to complete by April 2012. The findings from the study described in this paper have influenced the research design of the continuation study, and the emphasis has shifted to preservice elementary teachers attitudes towards mathematics and science, as well as their beliefs about their own potential efficacy to teach mathematics and science. During the intervention one of the 6th-grade teachers' used the video-conferencing software Skype to have her students ask an African engineer questions relevant to their wind turbine blade designs. This beneficial but unexpected incident provides some insight into the potential for future design partnerships in educational settings that have conventionally concentrated on collaboration at a more local scale.

It is hoped that the results presented in this study as well as the discussion of those results might be useful to other efforts with a similar agenda of studying the teaching and learning of contextualized STEM instruction. This study was designed to contribute to the body of research engaged in development and initial testing and assessment of innovative elementary and middle school contextualized STEM education that uses digital fabrication activities designed to incorporate STEM content.

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Appendix A -- Examples of Mathematics and Science Questions from Pretest and Posttest

Quantitative data collected from students included a mathematics and science content pretest (form A) at the beginning of the summer camp, and a mathematics and science content posttest (form B) at the end of the summer camp. An example of the paired multiple-choice mathematics question from the pretest was Figure 1 below:

The formula shows that *c*, the total cost of buying pizzas at Al's Restaurant, depends on *p*, the number of pizzas ordered.

$$c = 9p$$

What is the independent variable in the formula?

F p
G c
H 9
J =

Figure 1. Example of mathematics multiple-choice question from pretest.

An example of the paired multiple-choice mathematics question from the posttest was Figure 2 below:

Fran drove *m* miles in a car she rented. To find *R*, the total cost of renting the car, she used the following formula.

$$R = 0.50m + 35$$

What is the dependent variable in the formula?

A R
B 0.50
C m
D 35

Figure 2. Example of paired mathematics multiple-choice question from posttest.

An example of a multiple-choice science question from the pretest was Figure 3 below:

Crickets chirp to attract other crickets. The temperatures and rates of their chirping are graphed above. Which statement below is most likely true for the data represented in the graph?

F The cooler the temperature, the louder the crickets chirp.

G The crickets cannot chirp at temperatures lower than 10°C.

H The warmer the temperature, the more often crickets chirp.

J The temperature and the chirping of crickets are not related.

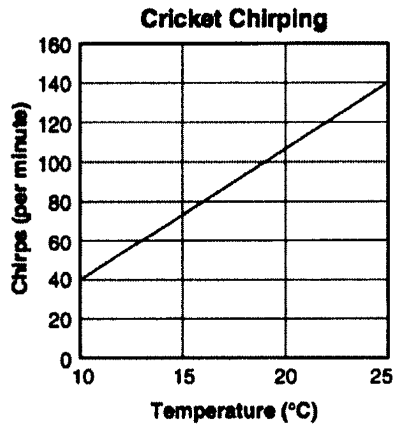

Figure 3. Example of science multiple-choice question from pretest.B

An example of the paired multiple-choice science question from the posttest was Figure 4 below:

The picture shows the growth curve of a bacterial population. According to this information, the bacterial population doubles every —

F 3 minutes

G 20 minutes

H 30 minutes

J 60 minutes

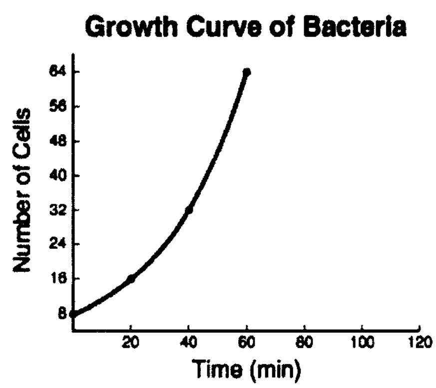

Figure 4. Example of paired science multiple-choice question from posttest.

Preservice Elementary Teachers' Science Teaching Efficacy Beliefs After Taking an Instructional Technology Course Featuring Digital Fabrication Activities

By Daniel A. Tillman, Gabriella J. Ducamp, and Crystal J. DeJaegher

Abstract

This study focused on ways in which an instructional technology course featuring digital fabrication activities impacted (1) preservice elementary teachers' efficacy beliefs about teaching science, and (2) their attitudes and understanding of effective approaches to integrating technology and digital fabrication into teaching science. The research compared two sections of course Teaching With Technology. One section integrated digital fabrication activities within an engineering education framework. Another section of the same course utilized a media cycle framework (Bull & Bell, 2005). Data collected for analysis included the Science Teaching Efficacy Belief Instrument and the preservice elementary teachers' answers to open-response questions about technologies they plan to use in their subsequent teaching. Two main results were supported by empirical evidence: (1) After completion of the three instructional technology courses, students in the sections featuring digital fabrication reported statistically significant overall gains in science teaching efficacy beliefs. (2) When asked to describe their future plans for using instructional technologies in their teaching, the top five most mentioned by the 28 participants in the digital fabrication sections were: interactive whiteboards (25 participants mentioned), video (16), class website (9), interactive online timeline (9), and digital fabrication (8). Of the eight participants who mentioned digital fabrication, the specific content areas mentioned were: history (4 participants mentioned), social studies

(2), science (1), math (1), engineering (1), and technology (1). The article concludes with a discussion of ways in which these results might provide guidance to further research.

Keywords: preservice elementary teachers, science teaching efficacy, digital fabrication

Introduction

This study investigated how an instructional technology course featuring digital fabrication impacted preservice elementary teachers' efficacy beliefs about teaching science, and their plans to use instructional technology and digital fabrication when teaching science in the future. This study was contextualized within a broader line of research inquiry probing the specific affordances as well as constraints of using digital fabrication within elementary science, technology, engineering, and mathematics (STEM) education.

The setting for this study was three sections of an instructional technology course for preservice elementary teachers taught during the fall 2011 and spring 2012 semester. Two of the sections featured digital fabrication, and one section was used as a comparison group. Digital fabrication is an instructional technology that leverages desktop manufacturing software and hardware to translate digital designs into physical objects (Bull & Groves, 2009). Digital fabrication has affordances that might be of benefit within several academic content areas, including elementary mathematics education (Berry et al., 2010) and elementary science education (Tillman, draft).

The present study focused on preservice elementary teachers, and the impacts of an instructional technology course featuring digital fabrication. The study analyzed ways in which this intervention affected preservice elementary teachers' efficacy beliefs about teaching science, and their plans to use instructional technology and digital fabrication to teach science. The research questions for this study were --

1. How does an instructional technology course featuring digital fabrication activities affect preservice elementary teachers' science teaching efficacy beliefs?
2. What are their plans to use instructional technology and digital fabrication activities within their science teaching in the future?

Literature Review

This literature review will first discuss previous research on preservice elementary teachers' science teaching efficacy beliefs. The review will then discuss digital fabrication hardware and software, and present a rationale describing how using digital fabrication to teach science might impact preservice elementary teachers science teaching efficacy beliefs.

Preservice Elementary Teachers' Efficacy for Teaching Science

Preservice elementary teachers have reported low efficacy beliefs for future science teaching (Bleicher, 2004). Inservice elementary teachers in the United States have reported believing that they lack sufficient science content knowledge, and confidence in teaching science concepts (Fulp, 2002). Participating preservice teachers had dispositions towards science and other STEM topics that were lower than the middle school students participating in the study (Knezek et al., 2011). Teacher attitudes towards STEM topics are relevant because they can sometimes affect pupils' attitudes towards the same STEM topics (Christensen, 2002). Part of the difficulty with increasing students' science achievement develops from the attitudes of both teachers and students towards the subject (Paulson, 2009). This can have long-term consequences. As students enter the workforce, those who avoided STEM courses often have difficulty succeeding in an increasingly STEM-oriented workplace (Hamilton, 2001).

Recognizing the importance of preservice elementary teachers' efficacy beliefs for teaching science, the Science Teaching Efficacy Belief Instrument (STEBI) was developed by Enoch and Riggs in 1990. Enoch and Riggs created the STEBI based upon Bandura's self-efficacy theory, believing that remediation of low science teaching efficacy beliefs was key to effective elementary teacher preparation programs. Since its creation, the STEBI has been used to measure preservice elementary teachers efficacy beliefs regarding teaching science in numerous studies. Increasing preservice elementary teachers' science teaching efficacy beliefs has been challenging. One potential avenue for addressing this issue is the use of digital fabrication for supporting science pedagogy.

Digital fabrication as an Instructional Technology

Digital fabrication enables the design and production of media content that spans several formats, from the virtual to the physical (Bull & Groves, 2009). Two-dimensional fabricators create designs out of materials like cardstock, magnetsheets, and vinyl; three-dimensional fabricators use malleable materials like silicone, playdoh, and chocolate, which then harden into solid objects (Malone & Lipson, 2007). Student-friendly digital fabrication hardware and software are instructional technologies that can be used by elementary teachers in science education (Tillman, draft). Research studies focused on digital fabrication have often taken place within extracurricular academic programs that took place during the summer (e.g., Ducamp, draft; Tillman & Cohen, draft). A few studies of the educational applications of digital fabrication have been conducted in the formal elementary classroom, but these have often occurred within the context of gifted education (e.g., Kjellstrom, draft).

One study took place in a formal classroom with 5th-grade students who had been recognized as advanced in mathematics. The main dependent variable studied was the students' knowledge of science content from the Virginia Standards of Learning (Tillman, draft). The study operated from a modeling-based instruction (MBI) theoretical framework. The MBI framework emphasizes student interactions with models of complex phenomena such as biological ecosystems. It was designed to be interwoven into the regular science curriculum (Buckley et., 2004). Based on the data collected, it was determined that student participants demonstrated significant positive gains in correct answers to questions on the topic of "Force, Matter, Energy, & Motion" from pretest to posttest, as well as on correct answers to select questions from the 5th-grade SOL exams (Tillman, draft).

To support such research the Fab@School Coalition (FSC) was created, consisting of a network of partners representing research universities (UVA, UNT, JMU, and Hofstra), education associations (ISTE, AMTE, ASTE, and ITEEA), and technology corporations (Graphtec, Aspex, and FableVision). The FSC mission is to facilitate integration of the instructional technology digital fabrication into education -- within formal classrooms, informal learning environments, and preservice teacher education. The FSC has identified four issues that need addressing for digital fabrication to become a scalable instructional technology. These are: (1) hardware and software, (2) curricula, (3) professional development and preservice teacher education, and (4) assessment. The present study focused on the education of future elementary teachers.

Research Design

Overview

This study collected data from a convenience sample of 42 preservice elementary teachers enrolled in one of three sections of an undergraduate course, Teaching With Technology, in the fall 2011 and spring 2012 semesters. Two sections of the course constituted the intervention group, and 25% of the class time was devoted to digital fabrication as an instructional technology. The third section of the course was a comparison group. It utilized the traditional content of the course that focused upon a media cycle framework (Bull and Bell, 2005).

This study employed a convergent parallel mixed-methods design in which both quantitative data as well as qualitative data were collected, analyzed separately, and then combined during interpretation. Quantitative data from participants who completed both a pre-intervention and a post-intervention Science Teaching Efficacy Belief Instrument (STEBI) survey were analyzed and used as evidence in support of the results posited as a response to research question one. Participants in the study also answered open-response questions at the conclusion of the course, which were analyzed to address research question two.

Setting

The setting for this study was the school of education at a medium-sized research university in central Virginia. Participants in the study were students in three sections of a Teaching With Technology course for preservice elementary teachers. Two sections were included in the study during the fall 2011 semester. One met from 5-7pm and the other met from 7-9pm. Another section of the course during the spring 2012 semester met from 4-6pm on Thursdays.

Participants

Participants in this study were preservice elementary teachers enrolled in one of three sections of a Teaching With Technology course. This course is generally during the junior or senior year of their undergraduate enrollment. Participation in the study was optional for all students involved. Students were informed that participation did not affect their final course grades. The intervention group contained 28 participants total, and the comparison group contained 14 participants.

Students enrolled in the fall 2011 5-7pm section and the spring 2012 section participated in the intervention, and devoted approximately one-quarter of the class time to developing and using digital fabrication as a strategy for teaching elementary students content from the curriculum, with an emphasis upon science. Students in the fall 2011 7-9pm section participated as the comparison group, and received a general curriculum that is traditionally taught in the course (and for purposes of equity, were given the option to engage in development of pedagogy using digital fabrication after the course was completed). Data collection for the study began August 2011, and completed April 2012.

The instructor for the fall 2011 intervention group was a graduate student and former teacher enrolled in a Ph.D. program specializing in instructional technology. Her previous teaching experience included nine years at an elementary school, where she taught second through fourth grade in all subject areas including science. The instructor for the fall 2011 comparison group and the spring 2012 intervention group was also a graduate student and former teacher enrolled in a Ph.D. program specializing in instructional technology. Her previous teaching experience included four years teaching English in a secondary setting, and two years teaching seventh and eighth grade students reading, English, and U.S. history.

Intervention

Preservice elementary teachers were introduced to digital fabrication as a strategy for teaching content, with an emphasis upon connections to science pedagogy. To support them in this effort they were provided: (1) approximately twenty-six hours of instruction of which approximately 25% was devoted to the intervention, (2) access to an online repository of digital fabrication based lessons that had already been developed and tested in schools, and (3) additional associated resources including instructional videos and responses to frequently asked questions (available at a website repository with address www.maketolearn.org). Two sections of the course participated as the intervention group, and spent approximately one-half of every other class period devoted to the use of digital fabrication as an instructional technology. Emphasis was placed upon connections to science pedagogy, but other content areas such as social studies and language arts were also surveyed. Participants engaged in activities that utilized affordances of digital fabrication, such as the ability to support the construction of physical models and rapid prototyping of designed objects. The course description from the syllabus for the intervention group stated: "This course provides pre-service teachers with a hands-on overview of technological tools which can be integrated and applied in a classroom setting to enhance the facilitation of teaching and student learning. The aim of this course is to provide the knowledge, training, and practice necessary to help you become teachers who innovate with technology."

Participants in the comparison group received the traditional Teaching With Technology course curriculum that is taught at the university utilizing the media cycle framework (Bull and Bell, 2005) and were not exposed to digital fabrication. The media cycle framework emphasizes a four-stage process for using media, as well as other instructional technologies, in the classroom: acquiring, analyzing, creating, and communicating. A consortium of professional educators developed this framework, and guidelines for application to the different content areas are available in a textbook published by ISTE. Participants in the comparison group were taught how to use the media cycle framework as a foundation for developing an understanding of effective use of instructional technology, and particularly digital media as an instructional technology.

Data Collection

Both quantitative and qualitative data were collected. The study participants completed the Science Teaching Efficacy Belief Instrument (STEBI) at one of the first classes and again at the end of the course, and also answered open-response questions at the conclusion of the course.

Quantitative -- Science Teaching Efficacy Belief Instrument (STEBI). The STEBI self-efficacy survey instrument focused on science teaching efficacy beliefs. Since its development by Enoch and Riggs (1990), it has been used in numerous studies to measure preservice elementary teachers efficacy beliefs regarding teaching science, as well as expectations regarding student outcomes from teaching science. It was based upon Bandura's self-efficacy theory, with the understanding that early detection and subsequent remediation of low teaching efficacy in elementary preservice teachers was critical to effective teacher preparation programs (Enoch & Riggs, 1990). The STEBI contained 25 items, 13 of which are part of the Personal Science Teaching Efficacy (PSTE) subscale, and 12 of which are part of the Science Teaching Outcome Expectancy (STOE) subscale. The PSTEBS is a sub-scale that focuses on the participants' personal science teaching efficacy beliefs, and the STOES is a sub-scale that focuses on the participants' beliefs about student outcomes.

Validity and reliability evidence collected by Enoch and Riggs from a sample of 212 preservice elementary teachers indicated that the STEBI was appropriate for obtaining a measure of preservice elementary teachers' science teaching efficacy beliefs (1990). Reliability was determined to have a Cronbach's alpha coefficient of 0.90 for the PSTE subscale, and a Cronbach's alpha coefficient of 0.76 for the STOE subscale. An item-total correlation was also determined, and showed values of 0.49 and above for all items on the PSTE subscale, and values of 0.30 and above for all items on the STOE subscale.

Construct validity evidence was determined via consultation with a panel of five science educators, who ensured item agreement and content validation in terms of integrity with the constructs measured, as well as a confirmatory factor analysis which determined the two subscales were modestly correlated ($r = 0.46$) (Enoch & Riggs, 1990). In 2004, Bleicher re-examined internal validity and reliability for the STEBI with a sample of 290 preservice teachers at the onset of a science methods course. Based upon a factor analysis, it was determined that the two subscales of Personal Science Teaching Efficacy Belief (PSTE) and Science Teaching Outcome Expectancy (STOE) were homogeneous, with loadings equivalent to those originally reported in 1990 by Enochs and Riggs.

Qualitative -- Open-Ended Question Answers. Qualitative data was collected via open-ended written response answers supplied in response to questions completed by the study participants. The participants answered questions focused on obtaining a gauge of their plans to use instructional technology when they are elementary classroom teachers. After completing the instructional technology course featuring digital fabrication, participants reported their plans for how to use instructional technologies in their teaching by answering the question: "Please describe three examples of how you would use technology in your teaching." The answers from participants in the intervention group were analyzed and coded using systematic data analysis (Miles and Huberman, 1994). The participants' self-reported answers to this question prompt were tabulated by instructional technology mentioned, and any specific content areas addressed.

Data Analysis and Results

The research design for this study emphasized collection and analysis of data addressing the two research questions. The next two parts of this section of the paper present results for each the research question.

Research Question 1: Participants' Science Teaching Efficacy Beliefs. Quantitative data collected from the STEBI administered at the beginning and conclusion of the intervention was analyzed to determine mean pretest score correct and mean posttest score correct. These averages were used to calculate percentage change as well as standard deviation for participants. These scores were then combined into an overall composite. A dependent (paired) samples t-test, with an assumed p-value of 0.05 and two-tails, was used to determine if any of the findings represent statistically significant results. Additionally, t-test scores for the two sub-scores were calculated using the same assumptions as for the main score.

After course completion, the intervention participants reported significant gains in overall science teaching efficacy beliefs as measured by the STEBI. Science teaching efficacy belief scores went up an average of 5.1% among the 28 preservice elementary teachers in the intervention group. A dependent (paired) samples t-test was used to determine the p-value of this change, and resulted in a calculation of $p = 0.004$, which based upon an assumed p-value of 0.05 and two-tails, represented a statistically significant result. This result can be compared to the average increase of 3.3% for the comparison group, which when using the same assumptions for a t-test resulted in a calculation of $p = 0.073$, a statistically non-significant result. It should be noted that two of the participants in the comparison group were enrolled in a science methods course in the fall 2011 semester. Table 1 below describes the overall results from the science teaching efficacy belief scores, separated into intervention and comparison groups.

Table 1

Results from Science Teaching Efficacy Belief Instrument (Intervention n = 28; comparison n = 14)

Group	Pretest score (s.d.)	Posttest score (s.d.)	% change	Dependent t-test
Intervention	85.9 (6.03)	90.3 (7.39)	5.1%	0.004*
Comparison	86.8 (7.95)	89.7 (7.79)	3.3%	0.073

* Denotes statistically significant with a two-tailed test at a p-value set to 0.05.

T-test scores for the two STEBI sub-scores were calculated using the same assumptions as for the main score. The Personal Science Teaching Efficacy Belief Scale (PSTEBS) consisted of 13 of the survey items. Results for the outcomes regarding the PSTEBS sub-score showed significant changes from the pre-intervention to the post-intervention assessment for the intervention group as well as the comparison group. Comparing the participants' responses showed that the PSTEBS sub-score went up an average of 6.2% among the 28 preservice elementary teachers in the intervention group. A dependent (paired) samples t-test, was used to determine the p-value of this change, and resulted in a calculation of $p = 0.008$, which based upon an assumed p-value of 0.05 and two-tails, represented a statistically significant result. This result can be compared to the average increase of 5.5% for the comparison group, which when using the same assumptions for a t-test resulted in a calculation of $p = 0.014$, also a statistically significant result. Table 2 below describes the overall results from the PSTEBS sub-scale of the STEBI, separated into intervention and comparison groups.

Table 2

Results from PSTEBS Sub-scores of the Science Teaching Efficacy Belief Instrument (Intervention n = 28; comparison n = 14)

Group	Pretest score (s.d.)	Posttest score (s.d.)	% change	Dependent t-test
Intervention	46.6 (4.92)	49.5 (5.22)	6.2%	0.008*
Comparison	47.3 (5.88)	49.9 (5.97)	5.5%	0.014*

* Denotes statistically significant with a two-tailed test at a p-value set to 0.05, though it should be noted that the comparison group had $n < 20$.

T-test scores for the Science Teaching Outcome Expectancy (STOE) sub-score of the STEBI was also calculated using the same assumptions as for the main score. The STOE sub-scale consisted of 12 of the survey items from the STEBI. Results for the outcomes regarding the STOE sub-score showed non-significant changes from the pre-intervention to the post-intervention assessment for the intervention group as well as the comparison group. Comparing the participants' responses showed that the PSTEB sub-score went up an average of 3.7% among the 28 preservice elementary teachers in the intervention group. A dependent (paired) samples t-test, was used to determine the p-value of this change, and resulted in a calculation of $p = 0.059$, which based upon an assumed p-value of 0.05 and two-tails, represented a statistically non-significant result. This result can be compared to the average increase of 0.9% for the comparison group, which when using the same assumptions for a t-test resulted in a calculation of $p = 0.804$, also a statistically non-significant result. Table 3 below describes the overall results from the STOE sub-scale of the STEBI, separated into intervention and comparison groups.

Table 3

Results from STOES Sub-scores of the Science Teaching Efficacy Belief Instrument

(Intervention n = 28; comparison n = 14)

Group	Pretest score (s.d.)	Posttest score (s.d.)	% change	Dependent t-test
Intervention	43.1 (3.45)	44.7 (4.60)	3.7%	0.059
Comparison	42.9 (4.29)	43.3 (4.87)	0.9%	0.804

Research Question 2: Participants' Plans for using Instructional Technology. The open-ended questions provided qualitative data that informed the second research question. This data was used to provide insight into student explanations of ways in which they plan to use instructional technology in their future teaching. Qualitative data was collected via participant answers to an open-ended question that focused on obtaining a gauge of the participants' self-reported plans to use instructional technology in teaching different content areas. Participant outcomes regarding their self-reported intentions to use instructional technology into their future teaching were tabulated according to instructional technology mentioned, and any specific content areas addressed. The top five most mentioned instructional technologies were then analyzed for number of students mentioning and percentage mentioning. This results section presents the participants' self-reported plans for using three instructional technologies in their teaching, including the most mentioned instructional technologies as well as number of students mentioning and percentage mentioning. It then presents the participants' self-reported plans for addressing specific content areas using the three instructional technologies they listed. Excerpts from participant answers are presented as examples of the type of responses that were provided.

Participant outcomes regarding self-reported intentions to use instructional technology in future teaching demonstrates that they each could describe a minimum of three instructional technologies that they felt would be valuable in their future teaching. The top five most frequently mentioned instructional technologies in the digital fabrication sections were: interactive whiteboards (25 participants mentioned), video (16), class website (9), interactive online timeline (9), and digital fabrication (8).

Additional instructional technologies that were mentioned more than once include: online comic creation (3 participants mentioned), blogs (3), Google Earth (2), and wikis (2). Instructional technologies that were mentioned once include: spreadsheets, prezi.com, brainpop.com, virtual field trips, laptop computers, interactive-clickers, and hands-on activities. Table 4 below describes the results from the participants' self-reported plans for using instructional technologies in their teaching.

Table 4

Top Results from Participants' Self-reported Plans for Using Instructional Technology into their Teaching (n = 28; each participant listed three technologies)

Instructional Technology	# Of Participants Mentioning	% Of Participants Mentioning
Interactive whiteboards	25	89.2%
Video	16	57.1%
Class website	9	32.1%
Online timeline	9	32.1%
Digital fabrication	8	28.6%
Online comic creation	3	10.7%
Blogs	3	10.7%

Participants' plans to utilize these technologies were sometimes focused on a particular content area, or several content areas, but sometimes did not mention any specific content areas. Of the 28 participants, 25 participants discussed plans to use interactive whiteboards in their teaching. [Appendix A contains tables 5, 6, 7, and 8 which depict the content areas specified by the participants for the top four most mentioned instructional technologies, as well as the full comments from the participants about the use of those technologies in their future teaching.] As an example of the use of interactive whiteboards, one of the participants stated: "I will definitely use the SMART technology for class presentations (assuming I have access to a SMART board). The activities available with this technology are very interactive and would effectively engage students." Sixteen participants discussed plans to use video in their teaching. As examples, one of the participants stated: "I would also use video making technology for student projects. Rather than just creating a project for me to see, the students would create videos to present to the class." Nine participants discussed plans to use a class website in their teaching. As examples, one of the participants stated: "The online collaborative websites seem like a really good way to engage students. Not only would they teach subject material, but they also make students more computer literate. So it would be useful in multiple ways." Nine participants discussed plans to use interactive online timelines in their teaching. As examples, one of the participants stated: "A technology that I will definitely use in my classroom is the timeline technology found online. This is so visual for students and will help give them a real picture of the timing of events in history."

Of the 8 participants who mentioned digital fabrication, the specific content areas mentioned were: history (4 participants mentioned), social studies (2), and science, math, engineering, and technology were each mentioned once (engineering and technology were both mentioned by the same participant). Only one participant who discussed digital fabrication did not mention a specific content area -- the lowest participant percentage of unidentified specific content areas of any of the top five mentioned instructional technologies. Table 9 below depicts the content areas specified by the participants in the digital fabrication section.

Table 9

Content Areas Mentioned for Application of Digital Fabrication (n = 8)

Content Areas	# Mentioning	% Mentioning
History	4	50.0%
Social Studies	2	25.0%
Science	1	12.5%
Math	1	12.5%
Engineering*	1	12.5%
Technology*	1	12.5%
No specific content area mentioned	1	12.5%

* Engineering and technology were both mentioned by the same participant.

Eight participants (28.6%) discussed plans to use digital fabrication in their teaching. As examples, one of the participants stated:

> "I would also use the more physical technologies that we tried, like creating the circuits and making the speakers. This is a way of translating what children learn and putting it into action. In this class, I've realized that a student can read about a topic as much as they want, but actually physically experience the topic provides a level of information absorption

that simple reading cannot achieve. Students take much more agency about circuits when they actually build one and hold it in their hands, as opposed to just reading about it. I would love to use this technique and idea for many different topics and technologies."

Another participant stated:

"Digital fabricators are a relatively new technology that I cannot wait to use in my classroom. First, it allows students to take ownership of their work. This tool helps develop a since of agency because while working with digital fabricators, students act as designers, educators, and builders. Second, digital fabricators take a concept and turn it into a reality. Students watch as a miniature world is build right before their eyes. For example, when student Native Americans, it may be difficult for some students to make the connections to societies that are no longer prevalent in most areas of the country. Instead of reading textbooks and looking pictures, digital fabricators allow the students to build an Indian village."

Another participant stated:

"In my science curriculum, I would most definitely replicate the windmill and speaker project we completed in class. I thought this was not only an engaging activity but also very fun and hands on. By creating and manipulating these materials, students can better understand the ways these technologies work and visualize the things they use in their daily lives."

A fourth participant stated:

"Another kind of technology that I would use as a teacher would be Diorama Designer. Students would create dioramas about a certain historical period. I think this lesson would help students learn history in greater detail and enable them to compare and contrast historical figures' lives and world to our own. Creating this kind of visual representation of a different era helps you identify with people of the past and important historical figures."

A fifth participant stated:

"Another way I might use technology in the classroom is through the Diorama Design program we learned and used in Technology class. I found this software very useful for teaching social studies. One way I might use it in teaching is when studying different lifestyles of people. For example, in 2nd grade students learn about three American Indian tribes and are to know the different home styles, food, and resources of each group. I might have students create each type of home using the diorama design to illustrate the differences between peoples."

Discussion

The previous results section addressed the two research questions individually, and presented the results from the data analysis as two separate parts. This section synthesizes results from the two research questions. Participants' self-reported gains in science teaching efficacy beliefs after the instructional technology course featuring digital fabrication were statistically significant. But of the eight students discussing digital fabrication in response to research question two, the content areas most mentioned regarding digital fabrication were: history (4 students mentioned) and social studies (2). Science, math, engineering, and technology were each mentioned only once as a content area, with engineering and technology both mentioned by the same participant. These results appear to indicate that while participants did have significant increases in science teaching efficacy beliefs at the conclusion of the instructional technology course featuring digital fabrication, this does not necessarily translate into plans to use digital fabrication in their future science teaching. Compared to digital fabrication, plans for teaching science were more prevalent among the 25 participants who mentioned interactive whiteboards, where science was addressed by eight of the participants (32.0%).

It is noteworthy that only one participant who discussed digital fabrication did not mention a specific content area. Of the top five mentioned instructional technologies this was the lowest participant percentage of unidentified specific content areas of any of the top five mentioned instructional technologies. These results appear to indicate that while only one of the intervention participants articulated a plan to use digital fabrication as an instructional technology for teaching science, most (all except for one) of the participants who did mention digital fabrication had at least one specific content area in mind. Conversely, no specific content areas were mentioned by any of the participants regarding class websites any of the nine times it was discussed, with the other three top mentioned instructional technologies falling between these two extremes. The content areas most mentioned regarding interactive whiteboards were: science, math, language art, and history. Eleven of the 25 participants who discussed interactive whiteboards did not identify any specific content areas. A partial explanation for the number of preservice teachers who discussed science teaching with interactive whiteboards may be several virtual science widgets that are included with the interactive whiteboard software.

The content areas most often mentioned regarding video were: history, science, and social studies, with 11 of the 16 participants discussing video not specifying any content areas. The content areas most mentioned regarding interactive online timelines were: history and social studies, with two of the nine mentioning interactive online timelines not specifying any content areas. These results appear to indicate that research with a similar agenda as the present study might find it challenging to impact preservice elementary teachers plans to prioritize using digital fabrication for teaching science in their future classrooms. Expanding the use of digital fabrication beyond the areas of comfort of the preservice elementary teachers, and into the realm of science and other STEM related areas, is a challenge for future efforts to expand digital fabrication into a larger educational context. The next section addresses limitations of the present study.

Limitations

There were several limitations to this study that adversely affected the outcomes obtained. The most notable of these limitations were: (1) the small sample size of the comparison group makes comparison to the intervention group difficult, (2) despite the use of a comparison group it was challenging to disentangle the impact of the digital fabrication from the impact of the course as a whole, and (3) the intervention might have had a greater impact if it consisted of a larger portion (> 25%) of the overall instructional technology course.

The small sample size of the comparison group makes comparison to the intervention group difficult. The intervention had a combined group of 28 participants that enabled analysis of pre-intervention and post-intervention quantitative data to meet the t-test assumption of having a sample size of 20 minimum. Because the sample size for the comparison group was only 14 participants, the t-test assumption of having a sample size of 20 minimum was not met, making analysis of the t-test results from the comparison group problematic, as noted in the paper when these results were presented earlier.

Despite the use of a comparison group it was challenging to disentangle the impact of the digital fabrication from the impact of the course as a whole. The comparison group did not show statistically significant impact on the overall STEBI. As described above, this is in part because the sample size did not meet the assumptions expected for a t-test.

The intervention might have had a greater impact if it consisted of a larger portion (> 25%) of the overall instructional technology course. The two sections of the course that participated in the intervention group spent a scheduled 25% of the class learning about digital fabrication as an instructional technology for facilitating elementary teaching. This percentage could be increased, for example, by allotting 50% (or more) of an instructional technology course to digital fabrication. These possibilities are discussed in the future research section that follows, which provides the concluding narrative description of this study.

Future Research

The federal government has undertaken a national initiative to increase focus on effective STEM education (Katehi et al., 2009). The present study was designed within this context. Specifically, this study aimed to contribute to the body of research focused upon supporting the development of future science professionals through the development and assessment of science pedagogical practices supported by innovative instructional technologies. This study was a continuation of a series of studies focused on the potential educational value of digital fabrication in the K-12 classroom. This study focused upon a population similar to a previous study that also had preservice elementary teachers as participants (i.e., Tillman et al., 2011). The current study builds upon and extends that work.

Plans for future research will continue this line of inquiry addressing the limitations discussed earlier. Further research will continue to focus on the impact of digital fabrication on STEM education. For instance, a continuation study involving digital fabrication in preservice elementary education in Western Texas is scheduled for implementation during the fall 2012 semester. That study will build upon the findings from the present study, addressing ways in which digital fabrication can impact science and STEM education efficacy beliefs of preservice elementary teachers.

Another future study will focus on the impact of digital fabrication in K-12 schools, including the upper-elementary classroom. This planned study is a continuation study of a previously published study (Tillman, draft), but the upcoming study will involve 4th-, 5th-, and 6th-grade students as participants, and will be undertaken with a sample of participants (n = 120, approximately) larger than that used in the previous studies cited in this article. The continuation study will also include a more prolonged exposure to digital fabrication as an instructional technology for supporting science teaching and learning. Participants in this continuation study will be upper elementary students in western Texas, the majority of who are of Hispanic ethnicity. Data collection for this planned study is also expected to commence in the fall of 2012, and be completed in the spring of 2013.

Similar to the future studies whose plans are described above, the current research study described in this paper was undertaken so as to advance a line of inquiry addressing the impact of digital fabrication as an instructional technology in the elementary classroom, as well as to facilitate guidance of future modifications to the "Teaching with Technology" courses taught at the institution where this study took place. The particular emphasis during the present study was upon science education, and impacts of a teaching with technology course featuring digital fabrication. This study was undertaken so as contribute to the line of research aimed at improving the education of future STEM professionals in the American workforce. The design and implementation of instructional technology courses for preservice elementary teachers that feature digital fabrication might, through empirical studies such as this one, demonstrate impacts that justify continued development and assessment.

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Appendix A -- Content Areas for Most Mentioned Instructional Technologies

Tables 5, 6, 7, and 8 below depict the content areas specified by the participants for the top four most mentioned instructional technologies. Each table is followed by quotes from the participants about their plans for use of those technologies in their future teaching. [The table and quotes with content areas specified by the participants for digital fabrication is included in the body of the article.]

Table 5

Content Areas Mentioned for Application of Interactive whiteboards (n = 25)

Content Areas	# Mentioning	% Mentioning
Science	8	32.0%
Math	8	32.0%
Language Arts	6	24.0%
History	4	16.0%
Social Studies	2	8.0%
Geography	2	8.0%
No specific content area mentioned	11	44.0%

Of the 28 participants, 25 participants (89.2%) discussed plans to use interactive whiteboards in their teaching. As examples, one of the participants stated:

> "One example of how I would use technology in my future teaching would be by using a SmartBoard or Promethian [sic] board. I think that this type

of technology is an excellent way to provide an interactive lesson that is engaging and interesting to students. I really enjoyed creating a lesson for a science SOL for our SmartBoard presentation, so I am inclined to continue to stick with teaching a science SOL by using a SmartBoard."

Another participant stated:

"One piece of technology that I plan to use will be the Smart Board. I have seen Smart Boards in various elementary classrooms before this class, but I have never had the chance to use the software. I was very helpful to play around with the program to gain a basic idea of how to use it. It was so interesting discovering the many ways to use Smart Board including the pre-made activities and different interactive tools. I think that Smart Board can be used for any content area."

A third participant stated:

"I will definitely use the SMART technology for class presentations (assuming I have access to a SMART board). The activities available with this technology are very interactive and would effectively engage students. It would be especially useful for quick review activities after teaching a lesson."

Table 6

Content Areas Mentioned for Application of Video (n = 16)

Content Areas	# Mentioning	% Mentioning
History	2	12.5%
Science	2	12.5%
Social Studies	1	6.3%
No specific content area mentioned	11	68.8%

Sixteen participants (57.1%) discussed plans to use video in their teaching. As examples, one of the participants stated:

> "I believe that as a teacher I will use videos to help students learn. I will assign a video project for students to compliment the given social studies standard of learning. For example, for the SOL that requires students to understand natural resources, students will be asked to make a video showing the natural resources of the local community along with one strategy to how to help conserve resources."

Another participant stated:

> "I would also use video making technology for student projects. Rather than just creating a project for me to see, the students would create videos to present to the class. This would provide further motivation because students always strive to impress their peers and feel as if there is more of

a reason to put maximum effort into the project to impress the class as a whole."

A third participant stated:

"Another way I would use technology in my teaching would be through the use of video cameras and recordings. When we did our video project, I thought it was extremely fun as a college student. The elementary students would hopefully find it even more entertaining, while still having to learn about the technology that accompanies filming and editing. I learned a lot of new things in that process, and the editing program was definitely simple enough for a student to use. Incorporating the Standards of Learning with a film project is a great idea because the students will be proactive in fulfilling their requirements, while still doing something that they consider fun, different, and exciting."

Table 7

Content Areas Mentioned for Application of Class Website (n = 9)

Content Areas	# Mentioning	%Mentioning
No specific content area mentioned	9	100.0%

Nine participants (32.1%) discussed plans to use a class website in their teaching. As examples, one of the participants stated:

"I would also like to implement a classroom website in my future classroom. Not only will this benefit my students, but it will also promote communication between me and their parents as well. I can create a classroom website through the use of google accounts and update it regularly with homework, the content we are learning, announcements, contact information, and extra resources for my students. I see this technology as a simple yet extremely effective way to promote technology while actually benefitting the classroom."

Another participant stated:

> "The online collaborative websites seem like a really good way to engage students. Not only would they teach subject material, but they also make students more computer literate. So it would be useful in multiple ways."

A third participant stated:

> "I would like to use a WikiSpace and/or Google site in my classroom…I'm not sure which yet. I really liked that WikiSpaces are able to be edited by users and I loved the discussion board function on WikiSpace, where students could post questions or comments. Google sites was more visually appealing (to me) though. I think a Google site would be a good place for a teacher to post stuff he/she needs to pull up in class (a document, a link, etc) and a good place for parents to go to see what their kids are doing in class."

Table 8

Content Areas Mentioned for Application of Interactive Online Timeline (n = 9)

Content Areas	# Mentioning	% Mentioning
History	5	55.6%
Social Studies	2	22.2%
Science	1	11.1%
Math	1	11.1%
No specific content area mentioned	2	22.2%

Nine participants (32.1%) discussed plans to use interactive online timelines in their teaching. As examples, one of the participants stated:

> "Another tool that I could use in my teaching would be Xtimeline. I have never seen this type of web site before, so I was very glad were introduced to this tool. Xtimeline is a great technology to use in social studies. It can visually show students the sequence of events in chronological order. Visualizing information helps some students who are visual learners acquire the knowledge more effectively."

Another participant stated:

> "A technology that I will definitely use in my classroom is the timeline technology found online. This is so visual for students and will help give them a real picture of the timing of events in history."

A third participant stated:

"Another example of how I would use technology in my future teaching would be by using a digital timeline. I thought that the X Timeline we experimented with in class would be a great way for students to create during a social studies unit. As the teacher, I would first create the timeline and include important dates that occur during the social studies unit I am teaching. As the unit progresses, my students and I would work together to add more information about these important dates."

Building Model NASA Satellites:

5^{th}-grade Advanced Mathematics Students Studying Science

Using a NASA-themed Transmedia Book Featuring Digital Fabrication Activities

By Daniel A. Tillman

Abstract

This study assessed the impact of lessons incorporating a NASA-themed transmedia book featuring digital fabrication activities on 5th-grade students recognized as advanced in mathematics. The main dependent variables were the students' knowledge of science content from the Virginia Standards of Learning, attitude towards science, and student reported likes and dislikes about the project. Data collected included a pretest and posttest of science content questions taken from released Virginia Standards of Learning exams, pre-intervention and post-intervention attitudinal survey data on students' attitude towards science, and open-response questions completed by students describing their likes and dislikes about the experience. Based upon analysis of the data collected, three main results were determined to have justifiable supporting empirical evidence: (1) Students demonstrated significant positive gains in correct answers to questions on the topic of "Force, Matter, Energy, & Motion" from pretest to posttest. (2) There were nonsignificant gains reported by students on the attitude survey questions about attitude towards science, but this was chiefly because of one question that was significantly impacted in a negative direction. (3) Students articulated five main categories of likes and six main categories of dislikes of the experience, thereby providing insight into their own perception of the affordances and constraints of the educational activities. The five topics mentioned most often by students as self-reported likes about the experience included: hands-on activities including building, making, or designing (18 of 29 students mentioned; 62.1%), experimenting (9 of 29; 31.0%), presenting (9 of 29; 31.0%), drawing (6 of 29; 20.7%), and working in groups (6 of 29; 20.7%). The six topics most mentioned by students as self-reported dislikes about the experience included: taking tests (13 of 29 students mentioned; 44.8%), confusing / too fast (7 of 29; 24.1%), drawing (4 of 29; 13.8%), class discussions (4 of 29; 13.8%), reviewing (4 of 29; 13.8%), and attitude surveys (4 of 29; 13.8%). The article concludes with a discussion of how these results might provide guidance to other endeavors that introduce transmedia books featuring digital fabrication activities in the context of science education.

Keywords: transmedia books, digital fabrication, upper elementary science education

Introduction

This article investigated the implications of a NASA-themed transmedia book featuring digital fabrication activities within upper elementary science education. The narrative theme of the transmedia book was NASA's Magnetospheric Multiscale (MMS) mission that will launch in 2014. During the spring 2012 semester, 5th-grade students (n = 29) identified as advanced in mathematics participated in a series of lessons based on the NASA-themed transmedia book. A transmedia book has many of the features of traditional books, but also has the capability of converting designs and images on the book's pages into physical objects through digital fabrication technology (Cohen, Smolkin, & Bull, 2012). An operational definition of digital fabrication is the use of student-friendly software and hardware to translate digital designs into physical objects

(Berry et al., 2010). The embedded digital fabrication activities within the transmedia book provided the students with multiple opportunities for experiencing hands-on investigations of various aspects of the MMS mission.

Within this context, this study was designed to investigate pedagogical and logistical aspects of implementing the NASA-based transmedia book, addressing four research questions:

1. What effects did a series of lessons using the NASA-themed transmedia book have on advanced mathematics 5th-grade students' knowledge of science content?
2. What effects were there on the students' attitudes towards science?
3. What were the students' self-reported likes about the experience?
4. What were the students' self-reported dislikes about the experience?

Literature Review

This study sought to investigate the impacts of a NASA-themed transmedia book. The primary theoretical framework for the study was modeling-based instruction of science content. Modeling-based instruction has been defined as a framework for teaching science via activities that involve students creating, using, and sharing models that highlight key aspects of complex scientific phenomena (Shen et al., 2010). This literature review has two main sections, the first of which discusses previous research on the use of modeling-based instruction of science content. The second section discusses previous research on the use of transmedia books featuring digital fabrication activities within educational settings, and presents a rationale for why transmedia books featuring digital fabrication activities are an appropriate instructional technology for supporting modeling-based instruction in upper elementary school science education.

Modeling-based Instruction of Science Content

Modeling-based instruction of science content emphasizes student interactions with models of complex phenomena, and is designed to be interwoven into the regular science curriculum. In this framework, a model is defined as a simplified representation of real-world phenomena (Buckley et al., 2004). Examples of models include: physical objects, videos, 2D and 3D animations, maps, and metaphors. These different types of models share the capacity to scaffold student learning as they develop a streamlined understanding of a complicated reality (Ainsworth, Prain, & Tytler, 2011). Models accomplish this by focusing the learner's attention on the significant aspects of complex phenomena (Feurzeig & Roberts, 1999). Models can vary in design and intricacy based upon the age and education of the user. Thus modeling-based instruction varies according to the age and education of the user, including both the types of models employed as well as how the models are utilized (Lohner et al., 2005).

The two key elements that characterize modeling-based instruction in science are: (1) the utilization of models constructed by or for the students, and (2) the educational activities that involve the models before, during, and after construction (Sengupta & Wilensky, 2009). Modeling-based instruction within science education often includes opportunities for students to articulate their understanding of the models via journaling, class discussion, group presentations, and artifacts of the physical or virtual models (Clement, 2008). These articulations can facilitate teachers in their efforts to foster students' construction of models that accurately represent key aspects of the real-world phenomena studied (Willensky & Reisman, 2006). Modeling-based instruction can facilitate student collaboration by allowing them to work simultaneously on the same modeling activity, providing both immediate feedback and insight into aspects of their thinking process (Lei et al., 2010). Researchers and teachers can also use analysis of the artifacts from student virtual and physical models to gain insight into the students' thinking and learning (Penner, 2001). Thus in modeling-based instruction, the model does not merely serve as a representation designed to convey information, but instead also serves as an anchor for teacher-student and student-student interactions through which the students can build correct understandings of scientific concepts and phenomena.

Student thinking and learning can be influenced by the nature of the models they work with, as well as the structure of the learning environment in which they interact with the models (Lohner et al., 2005). Use of modeling-based instruction for science education has been studied in both open (discovery-based) and semi-open learning environments (Schwartz et al., 2009). Open learning environments provide the students with flexibility in their choice of the aspects of the scientific phenomena the models they create will highlight, but this lack of direction can result in them focusing on unimportant or superficial aspects. Semi-open directed inquiry is designed to help students focus on aspects of the model that are pedagogically relevant. This study therefore aimed to interpret how students behave with semi-open modeling-based instruction in an upper elementary science education context.

Transmedia Books Featuring Digital Fabrication Activities as a Mechanism for Modeling-based Instruction of Science Content

This section of the literature review will present a synthesis of previous research focused on the potential of transmedia books as a mechanism for modeling-based instruction of science content. Transmedia books share many of the qualities of traditional books, but in addition they also provide users with the ability to utilize digital fabrication technology to convert designs and images from the book's pages into physical objects (Cohen, Smolkin, & Bull, 2012). A transmedia book titled "Make to Learn: Exploring Wind Energy" was used as a pedagogical tool for integration of mathematics, science, and engineering education. This transmedia book is based upon the story of a boy from Malawi named William Kamkwamba who built a functional wind turbine that brought electricity to his village. A free copy of the transmedia book, "Make to Learn: Exploring Wind Energy", is available to download from the *CITE Journal* (www.citejournal.org/articles/v11i3AppendixA.pdf).

Published empirical research on the use of transmedia books featuring digital fabrication activities within educational contexts is currently limited in scope. This is partially because both transmedia books and digital fabrication software and hardware technology are still undergoing the initial stages of diffusion, and consequently they have not yet achieved mainstream status. As these innovative technologies become more mature and robust, previous research on the nature of the diffusion of innovations indicates that they will achieve a wider dissemination outside of the group of early adopters (Rogers, 2003).

Early adopters of digital fabrication technology in education have recognized that one of the principal affordances of this instructional technology is support to students in the designing and manufacturing of physical objects. The technology allows them to produce media content spanning the virtual to physical spectrum (Bull & Groves, 2009). Early adopters in the field of mathematics education have suggested that digital fabrication can allow students to become inventors, creators, and builders (Berry et al., 2010). Mathematics education that incorporates digital fabrication activities has leveraged the pedagogical importance of physical contextualization through real-world applications of mathematics (Tillman & Cohen, draft). The National Council of Teachers of Mathematics has acknowledged the role of mathematics activities that contextualize mathematics learning. Students want to know how mathematics is applicable to their lives (Williams, 2007). Contextual mathematics has been recognized as a pedagogical strategy that allows students to understand mathematics through real-world connections (Sears & Hersch, 1999).

Digital fabrication as a mechanism for contextualizing mathematics has just begun to be researched empirically. There is even less empirical research on digital fabrication as a mechanism for modeling-based instruction of science content.

This literature review has presented an overview of some of the potential affordance and constraints of transmedia books and digital fabrication activities. Transmedia books featuring digital fabrication activities appear to provide a potential mechanism for modeling-based instruction in science. The present study is designed to provide an assessment of the intervention's impact on students' knowledge of science content, students' attitudes towards science, and teacher and student recognized likes and dislikes about the experience.

Research Design and Methodology

Overview

This study focused on ways in which student participants performed and reacted when presented with semi-open modeling-based instruction of science content using a NASA-themed transmedia book featuring digital fabrication activities. The specific context of the study was an elementary school in central Virginia, during the spring 2012 semester. Student participants in the study were 5th-graders who had been identified as advanced in mathematics. After completing the pre-intervention assessment instruments, they began lessons based on a NASA-themed transmedia book containing a series of hands-on science activities designed in consultation with NASA personnel by an associate professor of science education at James Madison University (JMU). The students learned about science via a NASA-themed transmedia book focused on the solar terrestrial probes project currently designated the Magnetospheric Multiscale (MMS) mission which will be launched in 2014 (the mission will be renamed prior to launch). Digital fabrication activities embedded in the transmedia book included building and experimenting with model satellites that were based on the design for the actual MMS satellites. The MMS mission involves four spacecraft that have been identically instrumented. The satellites will travel within the Earth's magnetosphere principally studying magnetic reconnection (Smith, 2012).

The study utilized a convergent parallel mixed-methods design during which both quantitative data as well as qualitative data was collected. Both data sets were analyzed separately, and then their results were combined during interpretation. The focus of the present study was identification of impacts upon students' science content knowledge, students' attitude towards science, and students' self-reported likes and dislikes about the experience. Data analysis for this study included the following: (1) Students' pretest and posttest science content answers were analyzed and used as evidence in support of the results addressing research question one pertaining to knowledge of science content; (2) analysis comparing the pre-intervention and post-intervention survey questions that measured attitude towards science were used to address research question two pertaining the students' attitudes towards science; and (3) analysis of the open-response question answers, written by students describing their likes and dislikes about the transmedia book featuring digital fabrication activities, were used to address research questions three and four on the students' self-reported likes and dislikes about the experience.

Setting

As described earlier, the data collected for this study was gathered at an elementary school in central Virginia during the spring 2012 semester. The students were 5th-graders who had been selected for the intervention based upon identification as advanced in mathematics. Participation in the study was optional for all students involved. It did not affect the students' final course grades. They met from a scheduled 9:50AM to 10:50AM session each Thursday of the semester. They also worked on the activities outside of the assigned meeting time both at school and at home. The students met in the classroom of a gifted resource teacher with the necessary digital fabrication equipment and other materials needed required for implementation of the activities in the NASA-themed transmedia book.

Participants

This study collected data from a convenience sample of 5th-grade students (n = 29) who were pulled from their homeroom classrooms to participate because they had been identified as advanced in mathematics. Approximately one-third of these students had also been identified as recognized gifted and talented. Of the students, 16 were female and 13 were male. The classroom was supported by a gifted resource teacher (GRT), the students' homeroom teacher, a teaching assistant supporting the homeroom teacher, and the researcher.

Intervention

The intervention included a sequence of sessions involving a NASA-themed transmedia book featuring digital fabrication activities that incorporated science content. These activities were initially conceptualized at the 2011 National Technology Leadership Summit (NTLS XII) and involved contributions from science education professors from several research universities, as well as NASA's MMS Education & Public Outreach (E/PO) Mission Lead. The lessons were subsequently refined by some members of the NTLS team including an associate professor of science education, as well as NASA personnel including the E/PO mission lead, and two NASA engineers.

During the intervention, students learned about digital fabrication software and hardware, as well as related materials and supports. This enabled them to complete lessons in which they designed and fabricated model MMS satellites. The materials included: sheets of 110 lb. cardstock, computer with the Silhouette Studio software, Silhouette digital fabricator, and a color printer. The students created model MMS satellites built from templates, as well as their own original model satellite designs. The intervention was designed to coincide with the learning objectives of the science topics that students would encounter during upcoming Virginia Standards of Learning assessment exams.

The transmedia book presented digital fabrication activities that involved, for example, an overview of NASA's Magnetospheric Multiscale mission, modeling magnetic reconnection, building electromagnets, magnetic field activities, design of solar panel layouts, analysis of data from solar paneled models, rocket trunk design, forms of energy, centrifugal force, and the satellites' pyramidal array deployment. As an illustration of the types of activities in the transmedia book, Figure 1 below shows a digital fabrication related design challenge involving creation of a model of a solar-powered satellite. In some cases the transmedia book also featured links to videos pertaining to the activities, and these were made accessible through the use of QR codes (an abbreviation of "Quick Response Codes") such as the one shown in Figure 2 below.

Design Challenge- Determine what shape for a rotating satellite will provide a steady minimum current output from solar panels on the outside given a fixed position light source.

Designs and Constraints:

- Satellite Shape. Use the 2D Fabricator to construct a series of basic 3D shapes that have sides that are large enough to hold the solar panels.
- A rotating surface for the satellite to be placed on.
    - Build your own in the 3D fabricator? With gears and an arm?
    - Use something pre-made? An old record turn-table?
- A way to connect the solar panels to an ammeter without getting the wires tangled as the platform and satellite rotate.
- A circle/disc shape is not to be tested as it is not a practical build shape.
- Your shape must maintain a minimum current output while it is rotating.

Questions to think about?

1. When will you get a maximum current output? What angle between the light source and solar panels would create this?
2. When will you get a minimum current output? What angle between the light source and solar panels would create this?

Figure 1. An example of a transmedia book design challenge involving digital fabrication to create models of solar-powered satellites.

Example: Need some help getting started with an idea? Here is an example of what a setup could look like:

Figure 2. An example of a QR code from the transmedia book linking to videos pertaining to the digital fabrication activities.

Table 1 below lists the sequence of lessons for the intervention, including the topics and objectives for each t-book section, as well as the associated digital fabrication related activities.

Table 1

Sequence of Lessons for Intervention

T-book section	Topics & Objectives	Digital Fabrication Related Activities
#1	Introduction to MMS t-book and overview of MMS mission	Modeling magnetic reconnection
#2	Introduction to magnetism	Magnet activities Student built electromagnets
#3	Introduction to magnetic fields	Magnetic fields activities
#4	Introduction to solar power	Solar panels design challenge Solar paneled models data collection Analysis of data collected
#5	Introduction to rockets	Fitting four satellites into rocket trunk Surface area to volume ratios activity
#6	Introduction to forms of energy	Modeling and discussing forms of energy using student fabrications
#7	Introduction to satellites' pyramidal array deployment	Model satellites design and fabrication Satellites suspension in pyramidal array
#8	Introduction to centrifugal force	Modeling centrifugal forces activity Centrifugal forces analysis
#9	Conclusion of NASA-themed MMS t-book activities	Student presentations on t-book Teacher led concluding discussion

Data Collection

Quantitative -- Science Content Pretest and Posttest. Students completed a science content pretest (form A) at the beginning of the intervention, and a science content posttest (form B) at the end of the intervention. Items were chosen from previously released Virginia Standards of Learning science tests, based upon alignment with the science content that was embedded in the digital fabrication activities presented in the transmedia book. The Virginia Standards of Learning have tremendous implications for Virginia schools. The results are included in the School Performance Report Cards from which accreditation status is determined (U.S. Department of State, 2012). Each question was paired with a matched, but not identical, SOL question on the pretest and the posttest based upon similar topic and difficulty. Selection and matching of items was facilitated and supervised by an associate professor of science education specializing in preservice teacher education. Both forms of the exam contained 25 content questions, all 25 of which were taken from previous Virginia Science Standards of Learning tests.

Three science areas tested: "Earth/Space Systems and Cycles", "Force, Motion, Energy, and Matter", and "Scientific Investigation". Ten questions on the pretest/posttest were from the "Earth/Space Systems and Cycles" area, of which five questions were from released 5th-grade SOL exams, four questions were from released 8th-grade SOL exams (wherein the questions are referred to as "Earth and Space Systems"), and one question was from released Earth Science SOL exams (wherein the questions are referred to as "Astronomy and Space Science"). Ten questions on the pretest/posttest were from the "Force, Motion, Energy, and Matter" area, of which seven questions were from released

5th-grade SOL exams, and three questions were from released 8th-grade SOL exams. Five questions on the pretest/posttest were from the "Scientific Investigation" area, of which two questions were from released 5th-grade SOL exams, two questions were from released 8th-grade SOL exams, and one question was from released Earth Science SOL exams. See Appendix A of this document for examples of paired multiple-choice science questions (Figure 3, 4, 5, and 6).

Quantitative -- Survey on Attitude Towards Science. Another source of quantitative data for the study was the science section of the STEM Semantics Survey (Knezek, Christensen, & Tyler-Wood, 2009). This survey includes a five-question section designed to assess attitude towards the field of science, each question of which utilized a Likert scale from 1 to 7 to allow the participant to indicate how they feel about the subject along a continuum of opposite descriptors. Student participants completed the science section of the "STEM Semantic Surveys" once at the beginning of the intervention, and then again at the end of the intervention. Students were given definitions of any words on the survey that they were unfamiliar with. Figure 7 below shows the science survey questions that the students answered.

To me, SCIENCE is:

1.	fascinating	①	②	③	④	⑤	⑥	⑦	mundane
2.	appealing	①	②	③	④	⑤	⑥	⑦	unappealing
3.	exciting	①	②	③	④	⑤	⑥	⑦	unexciting
4.	means nothing	①	②	③	④	⑤	⑥	⑦	means a lot
5.	boring	①	②	③	④	⑤	⑥	⑦	interesting

Figure 7. Survey questions answered by students about attitude towards science.

Tyler-Wood, Knezek, & Christensen (2010) presented validity and reliability evidence for the STEM Semantics Survey collected during the spring and summer of 2009. They collected baseline data from a purposely chosen wide range of pertinent convenience samples, including preservice K-12 teachers (n = 58), inservice K-12 teachers (n = 11), upper elementary and middle school students (n = 60), university professors (n = 14), and NSF project evaluators and primary investigators (n = 29). They used the data from these samples to judge the measures for both consistency and relevance, which they equated with reliability and validity respectively. The individual scales on the STEM Semantics Survey were determined to have a Cronbach's alpha ranging from 0.78 to 0.94, and these results were determined to be satisfactory indicators of internal consistency, and therefore reliability. They also assessed the STEM Semantics Survey for content validity, construct validity, and criterion-related validity, and determined that for all areas assessed it met acceptable benchmarks (Tyler-Wood, Knezek, & Christensen, 2010).

Qualitative -- Open-Response Question Answers from Students. Participating students in the study were asked to describe their likes and dislikes about using the transmedia book featuring digital fabrication activities as a mechanism for learning science content. The students performed this task by writing in journals which had been individually assigned, and that they had been using during the activities included in the intervention. The students first wrote in their journals about what their likes were regarding the experience. The students then wrote in their journals about what their dislikes were regarding the experience. Students were informed that if they had questions about the activity, then they should raise their hand and their questions would be addressed by one of the teachers. The open-response question answers that the students provided in their journals were used to inform research questions three and four regarding the student reported likes and dislikes about the experience.

Data Analysis

Quantitative -- Science Content Pretest and Posttest. Quantitative data collected from students included a science content pretest (form A) at the beginning of the intervention, and a science content posttest (form B) at the end of the intervention. Items were chosen based upon affiliation with the science content embedded in the digital fabrication activities. Quantitative data collected from the pretest and posttest was analyzed to determine mean pretest score correct and mean posttest score correct, and then these averages were used to calculate percentage change as well as standard deviation. All questions on the pretest and posttest were weighted equally, and assigned a value of 1 point if correct, and 0 points if incorrect. These scores were then combined into an overall composite for the entirety of the participants. A dependent (paired) samples t-test, with an assumed p-value of 0.05 and two-tails, was then used to determine if the overall score changes represented statistically significant results. The individual science questions were then combined by areas. These included the following three categories: "Earth/Space Systems and Cycles", "Force, Motion, Energy, and Matter", and "Scientific Investigation". A dependent (paired) samples t-test, with an assumed p-value of 0.05 and two-tails, was then used to determine if the score changes for the individual science areas represented statistically significant results. The individual science questions were then combined by exam type, which included the following three categories: "5th-grade", "8th-grade", and "Earth Science". A dependent (paired) samples t-test, with an assumed p-value of 0.05 and two-tails, was then used to determine if the score changes for the individual exam types represented statistically significant results.

Quantitative -- Science Attitude Survey, Pre- and Post-intervention. Quantitative data collected from the science section of the STEM Semantics Survey was analyzed to obtain an assessment of participants' self-reported attitude towards science. Scores were measured both before completing the intervention and after completing the intervention, using the instrument's Likert scale wherein 1 is the lowest score and denotes no interest and 7 is the highest score and denotes extreme interest. (Some questions used the reverse scale, but these scores were flipped prior to data analysis.) Mean scores and standard deviations were calculated for both the pre-intervention and post-intervention survey data, as well as the percentage change. Dependent (paired) samples t-tests using a two-tailed test with a p-value set to 0.05 were then analyzed to determine whether there were statistically significant differences between the pre-intervention and post-intervention scores. This entailed calculating the pretest mean and standard deviation, posttest mean and standard deviation, and percentage change between the pretest and posttest mean. A dependent (paired) samples t-test, with an assumed p-value of 0.05 and two-tails, was then used to determine if the score changes for any of the five individual science attitude questions represented statistically significant results.

Qualitative -- Open-Response Question Answers from Students. The answers from participating students in the program, who were asked to describe their likes and dislikes of the activities, were analyzed and coded using systematic data analysis (Miles and Huberman, 1994). Coding involved categorizing each student's statements according to the topics mentioned, and then tabulating the number of students who mentioned a particular like or dislike. The categories of topics represented in the student answers to the open-response question answers were then summarized, including the most mentioned topics as well as number of students mentioning and percentage of students mentioning. Categories of likes and categories of dislikes were tallied in the student responses. Student quotations discussing each of the individual likes and dislikes mentioned were aggregated into categories divided by topic, and listed in descending order by number of students mentioning. This data was used to inform research questions three and four on the student reported likes and dislikes about the experience of using a NASA-themed transmedia book featuring digital fabrication activities as a mechanism for learning science education.

Results

The research design for this study stressed collection and analysis of data providing empirical evidence addressing the research questions pertaining to the pedagogical and logistical aspects of implementing the NASA-based transmedia book. The next four parts of this section of the paper present results addressing the four research questions individually.

Research Question 1: Impact on Students' Knowledge of Science Content

The transmedia book featuring digital fabrication activities resulted in non-significant overall gains in students' science test scores from pre-intervention to post-intervention. Comparing the students' pretest and posttest answers showed that science scores went up an average of 2.9% among the 29 students participating in the study.

These results were not statistically significant. Table 2 below describes the overall results from the science content questions.

Table 2

Results from Twenty-five Science Questions on Pretest and Posttest (n = 29)

Pretest correct	Posttest correct	Stan. dev. (pretest)	Stan. dev. (posttest)	% change	Dependent t-test
21.3	21.9	1.93	2.47	2.9%	0.084

Three science areas were tested: "Earth/Space Systems and Cycles", "Force, Motion, Energy, and Matter", and "Scientific Investigation". Responses to the ten questions on the pretest/posttest from the "Earth/Space Systems and Cycles" area went up an average of 3.5%. Responses to the ten questions on the pretest/posttest from the "Force, Motion, Energy, and Matter" area went up an average of 9.5%. The five questions on the pretest/posttest from the "Scientific Investigation" area decreased an average of -5.6%. The results from the "Force, Motion, Energy, and Matter" area were statistically significant. Table 3 below describes the results from each of the three science content areas.

Table 3

Results from Questions on Pretest and Posttest Separated by Content Area (n = 29)

Content area	# Qs	Pretest correct	Posttest correct	Sta. dev. (pretest)	Sta. dev. (posttest)	% change	Dependent t-test
Earth/Space Systems	10	8.5	8.8	0.97	1.32	3.5%	0.187
Force, Motion, Energy & Matter	10	8.2	8.8	1.10	1.20	9.5%	0.003*
Scientific Investigation	5	4.6	4.3	0.56	0.70	- 5.6%	0.057

* Denotes statistically significant with a two-tailed test at a p-value set to 0.05.

This same data can also be presented according to the grade level of the SOL questions. The questions on the pretest/posttest were drawn from previous released Virginia SOL exams, with fourteen of the questions coming from 5th-grade exams, nine of the questions coming from 8th-grade exams, and two of the questions coming from Earth Science exams. The fourteen questions on the pretest/posttest from the released 5th-grade exams went up an average of 6.8%. The nine questions on the pretest/posttest from the released 8th-grades exams went down an average of -3.8%. The two questions on the pretest/posttest from the released Earth Science exams went up an average of 18.5%. The results from the 5th-grade exam questions were statistically significant, though it should be noted that the 5th-grade exam questions overlap considerably with the "Force, Motion, Energy & Matter" questions from the previous table. Therefore Table 4 below describes the results from each of the three SOL exam types, but should be understood as a reiteration of the data from Table 3 that was discussed earlier and not as distinct data from Table 3.

Table 4

Results from Questions on Pretest and Posttest Separated by Exam Type (n = 29)

Exam type	# Qs	Pretest correct	Posttest correct	Sta. dev. (pretest)	Sta. dev. (posttest)	% change	Dependent t-test
5th-grade SOL	14	11.9	12.7	1.28	1.34	6.8%	0.005*
8th-grade SOL	9	8.0	7.7	1.00	1.29	-3.8%	0.106
Earth Science	2	1.4	1.6	0.62	0.57	18.5%	0.161

* Denotes statistically significant with a two-tailed test at a p-value set to 0.05.

Research Question 2: Impact on Students' Attitudes towards Science

There was a non-significant impact on students' self-reported attitudes towards science, with the student participants reporting an average -2.0% decreased positive attitude towards science after the intervention. Table 5 below reports the overall results from the science questions asked on the attitude survey.

Table 5

Overall Results from Science Questions on Attitude Survey (n = 29)

Pre-survey mean	Post-survey mean	Stan. dev. (pre-survey)	Stan. dev. (post-survey)	% change	Dependent t-test
30.2	29.1	4.75	4.48	-2.0%	0.209

The survey contained five individual questions on the topic of science, asking the student if they felt that "To me, SCIENCE is:" (1) fascinating or mundane, (2) appealing or unappealing, (3) exciting or unexciting, (4) means a lot nothing or means, and (5) interesting or boring. Students were given definitions of any words they did not understand, and then students indicated if they had positive attitudes towards science by marking a high of 7, or a low of 1 (after reversed questions were inverted for data analysis). On the individual questions, there were non-significant results for four of the individual questions, but one of the questions displayed a statistically significant negative results. This was the question about whether science was exciting or unexciting. Table 6 below describes the results from each of the five individual science attitude questions.

Table 6

Results from Individual Science Questions on Attitude Survey, with 7 as Highest Positive and 1 as Lowest Negative (n = 29)

Feels science is ...	Pre-survey mean	Post-survey mean	Sta. dev. (pre-survey)	Sta. dev. (post-survey)	% change	Dependent t-test
Fascinating	6.0	5.9	1.13	1.03	- 1.2%	0.722
Appealing	5.8	5.6	1.03	1.15	- 4.2%	0.345
Exciting	6.1	5.6	0.94	1.24	- 7.9%	0.014*
Means a lot	6.1	5.9	1.12	1.13	- 4.6%	0.275
Interesting	6.1	6.1	1.36	0.98	- 0.7%	0.896

* Denotes statistically significant with a two-tailed test at a p-value set to 0.05.

Research Question 3: Students' Self-reported Likes About the Experience

Students participating in the study wrote in their journals at the conclusion of the intervention about their likes regarding the experience. Table 7 below describes the results from the students' self-reported likes about the experience, including the most mentioned topics as well as number of students mentioning and percentage mentioning.

Table 7

Results from Students' Self-reported Likes about the Experience (n = 29)

Likes	# Of Students Mentioning	% Of Students Mentioning
Hands-on activities including building, making, or designing	18	62.1%
Experimenting	9	31.0%
Presenting	9	31.0%
Drawing	6	20.7%
Working in groups	6	20.7%

Of the 29 students, 18 students (62.1%) discussed liking hands-on activities including building, making, or designing. As examples, one of the students stated: "I really liked building the satelites [sic] and the presentations. I also liked the drawings that we did." Another student stated: "I liked making the satelites [sic] for the classroom presentation." A third student stated: "I liked the satalite [sic] building. I also liked the hands on projects, like the tape, magnet, and the presentation project." One of the students stated: " I liked how we made the four satilites [sic] and made a presentation. I really liked the whole class of M.M.S. It was really fun for my first project." Another student stated: "Some things I liked that about the NASA project was when we made the sattelites [sic] and when made the presentation." Another student stated: "I liked making the satalites [sic]. I also liked learning about the MMS mission." A fourth student stated: "Like enjanering [sic] the satalites [sic]." Another student stated: "I liked making modles [sic] of satalights [sic], doing experiments with solar panels, learning about the MMS mission, working with groups, learning about the radiation from the sun hitting earths magnetic field, getting to play with magnets, and making a magnet out of a nail, wire, and tape." Another student stated: "I liked the hands on projects becuse [sic] they were interesting and made the thery [sic, theory] make more sence [sic, sense]."

Of the 18 students that mentioned liking hands-on activities, five students specifically discussed liking the digital fabricator. As examples, one of the students stated: "I liked the digatal [sic] fabercater [sic]. It was fun to put together, but it was challenging, too! ... I really liked all of the NASA projects that we did. They were all fun!" Another student stated: "Liked making satelites [sic] with Silhouette Studio, liked working groups, rubber band activity." A third student stated: "I loved everything!!!! I loved the fabricator the very most!!!"

Nine students (31.0%) discussed liking experimenting. As examples, one of the students stated: "I liked doing the experiments with magnets, doing the energy presentations, and making the satellites." Another student stated: "I liked the models of the MMS and the expirements [sic] with gravity. I also liked learning about STEM." A third student stated: "I liked the rubber band experiment, and the tape one." Another student stated: "I liked the MMS and the experiments like the rubber band and clips and battery-powered magnets." Another student stated: " I liked when we did the magnetic expierements [sic]."

Nine students (31.0%) discussed liking presenting. As examples, one of the students stated: "I liked when we moved around and got up and worked on the satelights [sic] and when we did the skits. I liked working in groups." Another student stated: "I liked when we did the presintations [sic]."

Six students (20.7%) discussed liking drawing. As examples, one of the students stated: "I liked doing the experiments where we showed examples of things. I like drawing the STEM stuff." Another student stated: "I did like the digital fabricater [sic], drawing pics [sic], slides, building satalites [sic], talking about satalites [sic]."

Six students (20.7%) discussed liking working in groups. As examples, one of the students stated: "" I realy [sic] liked the play that we did for the energy. I liked it because you could get into a group you choosed [sic] and you got the work together." Another student stated: " I really liked the hands on activitys [sic] and working in groups. I also liked the digital fabricator projects."

Three students (10.3%) discussed that they liked everything (this was not counted towards the other categories). As an example, one of the students stated: "I liked the drawing, projects, and well everything." Another student stated: "I liked learning about the MMS mission. I also liked learning everything else almost." A third student stated: "Liked everything but the tests."

Research Question 4: Students' Self-reported Dislikes About the Experience

Students participating in the study also wrote in their journals at the conclusion of the intervention about their dislikes regarding the experience. Table 8 below describes the results from the students' self-reported dislikes about the experience, including the most mentioned topics as well as number of students mentioning and percentage mentioning.

Table 8

Results from Students' Self-reported Dislikes about the Experience (n = 29)

Dislikes	# Of Students Mentioning	% Of Students Mentioning
Taking tests	13	44.8%
Drawing	7	24.1%
Class discussions	4	13.8%
Confusing / too fast	4	13.8%
Reviewing	4	13.8%
Attitude surveys	4	13.8%

Of the 29 students, 13 students (44.8%) discussed disliking the assessment tests. As examples, one of the students stated: "There was nothing I disliked!!! But didn't like the tests or surveys." Another student stated: "I did not like the tests." A third student stated: "Didn't like the tests." Another student stated: "I didn't like learning about all the energy or taking the tests."

Seven students (24.1%) discussed disliking drawing. As examples, one of the students stated: " I didn't like drawing alot [sic]. I didn't like how long it was." Another student stated: " I didn't like drawing that much in our notebook. I kinda [sic] enjoyed how we drew the people, but I didn't like the STEM drawings. " A third student stated: "I didn't like drawing pictures."

Four students (13.8%) discussed disliking class discussions. As examples, one of the students stated: "I didn't like when we talked forever and when we took test." Another student stated: "I didn't like when we had to draw and when we had to take the tests. I also didn't like when we just sat there and talked about MMS."

Four students (13.8%) discussed disliking that things were confusing or too fast. As examples, one of the students stated: " I know the class has to go fast but sometime it is alot [sic] of information all at once." Another student stated: "Everything was, in my opinion, ok. Except for going fast or how long it took." A third student stated: "I didn't like going so fast because it got confusing."

Four students (13.8%) discussed disliking reviewing the lessons. As examples, one of the students stated: "What I didn't like was that we kept repeating things over and over." Another student stated: "Didn't like some of the experiments, listening ... Being bored."

Four students (13.8%) discussed disliking the attitude surveys. As examples, one of the students stated: "I didn't like having to do the tests on how we felt." Another student stated: "I didn't like the surveys and tests." Another one of the students stated: "I didn't like electricity project, working in groups, tests!, self evaluation sheets."

Two students (6.9%) discussed disliking working in groups. As examples, one of the students stated: "What I didn't like was some of our group members were messing around. " Another student stated: "I didn't like it because it was a little unorganized." A third student stated: "I don't really like working in groups."

Two students (6.9%) discussed disliking learning of danger (one student mentioned magnetic fields, and the other student mentioned cosmic radiation -- both examples demonstrate student scientific misconceptions). One of the students stated: "I didn't like it when we learned about radiation, and that in about a thousand years the human race will melt." Another student stated: "There was only one thing that I didn't like. I didn't like how [teacher] told us that if the magnetic field broke, we would all melt." It should be noted that neither of these student misconceptions is scientifically accurate, and both statements are examples of students misunderstanding what the teacher had said.

Three students (10.3%) discussed disliking nothing about the experience. As examples, one of the students stated: "I had no dislikes." Another student stated: "Nothing I didn't like."

Discussion

The empirical evidence presented in the previous section yielded three noteworthy results. The three results that had supporting empirical evidence were: (1) Students demonstrated significant positive gains in correct answers to questions on the topic of "Force, Matter, Energy, & Motion" from pretest to posttest. (2) There were nonsignificant gains reported by students on the attitude survey questions about attitude towards science. This was chiefly because of one question that was significantly impacted in a negative direction. (3) Students articulated five main categories of likes and six main categories of dislikes of the experience, thereby providing insight into their own perception of some of the affordances and constraints of the educational activities. In this section, the three results and supporting data presented in the previous results section are examined with respect to how they address the research questions.

Research Question 1: Impact on Students' Knowledge of Science Content

The NASA-themed transmedia book featuring digital fabrication activities resulted in statistically significant gains for the fourteen questions from the released 5th-grade SOL exams, as well as the ten questions from the "Force, Motion, Energy, and Matter" content area (of which six were from 5th-grade SOL exams, and four were from 8th-grade SOL exams). Student improvement in correctly answering the ten questions from the "Force, Motion, Energy, and Matter" science questions was consistent with the content from this area that paralleled many of the activities included in the intervention. The lack of significant improvement on 8th-grade SOL examination or Earth Science SOL examination questions indicates that despite their advanced ability in mathematics they are perhaps not developmentally ready for the more advanced science questions. It is also possible that the more advanced science content was not effectively taught through the intervention.

Research Question 2: Impact on Students' Attitudes towards Science

There was non-significant impact on students' self-reported attitudes towards science, with the student participants reporting an average -2% decrease in positive attitude towards science after the intervention. Of the five questions on this topic that students were asked, there was only statistically significant decrease in positive attitude -- feeling science is exciting or unexciting. This significant decrease in excitement towards science was possibly because the students had developed an increased awareness of the focus and hard work necessary to complete science activities.

Research Question 3: Students' Self-reported Likes About the Experience

The results from the students' self-reported likes including the most mentioned topics and percentage of students mentioning, provides insight into the students' processing of the experience. Five topics were mentioned most often by students as self-reported likes about the experience, including: hands-on activities including building, making, or designing (18 of 29 students mentioned; 62.1%), experimenting (9 of 29; 31.0%), presenting (9 of 29; 31.0%), drawing (6 of 29; 20.7%), and working in groups (6 of 29; 20.7%).

Research Question 4: Students' Self-reported Dislikes About the Experience

Likewise, the results from the students' self-reported dislikes, including the most mentioned topics and percentage of students mentioning, also provides insight into the students' processing of the experience. Six topics were most mentioned by students as self-reported dislikes about the experience, including: taking tests (13 of 29 students mentioned; 44.8%), drawing (7 of 29; 24.1%), confusing / too fast (4 of 29; 13.8%), class discussions (4 of 29; 13.8%), reviewing (4 of 29; 13.8%), and attitude surveys (4 of 29; 13.8%).

Limitations

There were several limitations to this study that affected the outcomes obtained. These limitations might partially explain some of the non-significant results. The most notable of these limitations were: (1) The study would have benefited from better alignment between the science content SOL questions administered during the pretest and posttest with the science that the students learned during the intervention. This might have negatively impacted results obtained in some of the areas tested, including "Earth/Space Systems and Cycles" and "Scientific Investigation" neither of which improved significantly. (2) The students might have experienced a ceiling effect on some of the science content topics. The pretest examination questions may have been insufficiently challenging resulting in limited room for significant improvement. (3) A third limitation -- a limitation not of the study, but of the intervention itself -- was that a once-per-week intervention may be insufficient exposure for influencing students' self-reported changes in attitude towards science and science content. This section next addresses these three limitations individually.

Students' correct responses to questions from the areas of "Earth/Space Systems and Cycles" and from "Scientific Investigation" did not improve significantly. The study would have benefited from better alignment with the science that the students learned during the intervention and the assessment. This improved alignment might have been achieved through both more congruent content and more congruent vocabulary. This might have negatively impacted results obtained in some of the areas tested including "Earth/Space Systems and Cycles" and "Scientific Investigation".

A second limitation to this study is that some students might have experienced a ceiling effect on portions of the science content quantitative assessment. All four of the students' homeroom teachers reported that they had students participate in practice Virginia science SOL examinations during the school year prior to the intervention. This might have artificially inflated the students' pretest exam scores on science content from the Virginia SOLs. These two limitations to the research study's design, combined with the limitation to the intervention described in the paragraph that follows, might partially explain some of the results from this study.

A third limitation is that a once-per-week intervention may be insufficient exposure for influencing students' self-reported changes in attitude towards science. The chief decrease in student positive attitude towards science was on the question about feeling science is exciting or unexciting. This was the only statistically significant decrease of the five individual questions. This significant decrease in excitement towards science was possibly because of the students' increased awareness of the hard work and focus required to actively participate in science activities. Increased exposure during any future interventions might help students see the value of participating in science, as the increased time might give them the opportunity to transition from believing science is mysterious or magical (and therefore "exciting"), to believing that science is a concerted human effort achieved through hard work and discipline (and therefore "means a lot").

Future Research

This project was intended as a launching point for further studies on the impacts of transmedia books featuring digital fabrication activities. The study aimed to provide useful information to: (1) researchers addressing the pedagogical affordances and constraints of implementing science education using transmedia books featuring digital fabrication activities, (2) preservice and inservice teachers considering or actively implementing related science activities in the classroom or informal settings, and (3) instructional designers and curriculum developers involved in the design and development of similar science education activities. There is much to learn about the pedagogical and logistical aspects of implementing modeling-based instruction of science content using transmedia books featuring digital fabrication activities, and this study had the purpose of contributing to elucidation of research questions relevant to this objective.

Plans for future research aim to continue within the line of inquiry presented in this study, and will strive to address the research limitations discussed earlier so as to minimize their influence. Further research will focus on understanding the impact of transmedia books featuring digital fabrication activities in other educational contexts, as well as with other populations. A continuation study involving a more prolonged exposure to a similar, but refined, intervention is therefore currently being designed, and will be undertaken with a larger sample of participants (n = 120, approximately). Participants will be upper elementary students in western Texas, the majority of who are Hispanic. Data collection for this planned study is expected to begin November 2012.

This research study was undertaken so as to advance a line of inquiry addressing the value of transmedia books featuring digital fabrication activities as a pedagogical tool in the upper elementary classroom. Like the other two studies in this three-paper manuscript-style dissertation, this study also aimed to contribute to the body of research focused upon improving the education of future STEM professionals. It is hoped that the results presented in this current study, as well as the discussion of those results, might be useful to other efforts with a similar agenda of examining the use of transmedia books featuring digital fabrication activities within education.

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Appendix A -- Examples of Science Questions from Pretest and Posttest

Quantitative data collected from students included a science content pretest (form A) at the beginning of the intervention, and a science content posttest (form B) at the end of the intervention. Matched, but not identical, SOL questions on the pretest and the posttest were paired based upon similar topic and difficulty. Each exam contained 25 content questions, borrowed from three science areas tested on previous Virginia Science Standards of Learning exams: "Earth/Space Systems and Cycles", "Force, Motion, Energy, and Matter", and "Scientific Investigation". Figure 3 below shows an example of the paired multiple-choice science question from the pretest.

The magnetic fields of any magnet are *greatest* —

A around the middle
B around the poles
C around only the south pole
D around only the north pole

Figure 3. Example of science multiple-choice question from pretest.

An example of the paired science question from the posttest was Figure 4 below.

A bar magnet is placed on a table, and a sheet of blank paper is placed over the magnet. What could be sprinkled on the paper to show the magnetic field of the bar magnet?

F Salt
G Iron filings
H Sand
J Soil

Figure 4. Example of paired science multiple-choice question from posttest.

Figure 5 below is another example of a multiple-choice science question from the pretest.

Astronomers view objects in space through scientific instruments known as —

A microscopes
B hygrometers
C telescopes
D barometers

Figure 5. Example of science multiple-choice question from pretest.

An example of the paired science question from the posttest was Figure 6 below.

The science of astronomy is concerned with the observation and analysis of the movements of celestial objects. The invention of which instrument was *most* helpful to the advancement of astronomy?

A Telescope
B Microscope
C Camera
D Geiger counter

Figure 6. Example of paired science multiple-choice question from posttest.