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RESEARCH REPORT

Engineering Design and Conceptual Change in Science: Addressing thermal energy and heat transfer in eighth grade

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The purpose of this research was to investigate the impact of engineering design classroom activities on middle-school students' conceptions of heat transfer and thermal energy. One eighth-grade physical science teacher and the students in three of her classes participated in this mixed-methods investigation. One class served as the control receiving the teacher's typical instruction. Students in a second class had the same learning objectives, but were taught science through an engineering design curriculum that included demonstrations targeting specific alternative conceptions about heat transfer and thermal energy. A third class also used the engineering design curriculum, but students experienced typical demonstrations instead of targeted ones. Conceptual understandings of heat transfer and thermal energy and attitudes towards engineering were assessed prior to and after the interventions through interviews, observations, artefact analysis, a multiple choice assessment, and a Likert scale assessment. Results indicated that the engineering design curriculum with targeted demonstrations was significantly more effective in eliciting desired conceptual change than the typical instruction and also significantly more effective than the engineering curriculum without targeted demonstrations. Implications from this study can inform how teachers should be prepared to use engineering design activities in science classrooms for conceptual change.

Keywords: *Alternative conceptions; Engineering design; Heat transfer; Middle school; Energy; Conceptual change*

Introduction

One important goal of science education is to feed the research pipeline with a steady supply of scientists and engineers that will tackle the global twenty-first

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century issues we face, i.e. energy shortages, environmental decline, climate change, natural resources, nutrition, and world health (Trefil, 2008). Perhaps even more important is the goal of current reforms to increase scientific and technological literacy for all, not just for future scientists and engineers.

In order to promote scientific and technological literacy, reform efforts in science education stress a change in emphasis towards active, inquiry-based learning (AAAS, 1993; NRC, 1996). The active process of learning involves both mental activities and physical activities as students work with their teachers and peers and interact with the learning environment (Bryson & Hand, 2007; NRC, 1996). While engaged in active learning, students can make gains in content knowledge, scientific process skills, and attitudes towards science. In general, active learning reaches students who possess a wide variety of learning styles, much more so than traditional teaching and learning, as students think about and perform meaningful activities (Bransford, Brown, & Cocking, 2000).

However, even with active, inquiry-based learning, students and adults alike have a difficult time understanding many scientific explanations of natural phenomena (Brown, 1992; Clement, 1993; Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Vosniadou & Brewer, 1992; Wandersee, Mintzes, & Novak, 1994). This is an obvious obstacle to scientific literacy. People may hold onto their own invented theories for a lifetime. In order for conceptual change to take place, a learner must become dissatisfied with his alternative conceptions, then grasp an intelligible new conception and use that conception to solve a problem (Posner, Strike, Hewson, & Gertzog, 1982). Many methods for helping students with conceptual change in science have been implemented, some more successfully than others. With the current and popular integration of science, technology, engineering, and mathematics in K-12 curricula, some have suggested that engineering design could facilitate desired construction of scientific knowledge and have attempted to design curriculum to do so (Fortus, Dershiimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner et al., 2003).

Since the Sputnik era, universities and professional organizations have developed dozens of engineering education programmes for pre-college students to help them understand what engineers do, teach them about the engineering design process, and target deficits in scientific and technological literacy. However, there is a paucity of research on how effective these are at helping students actually learn important science concepts, how learning outcomes may differ from those of traditional teaching pedagogies, and there is virtually no research on how engineering design activities might promote conceptual change in science (Chaker, 2008; Katehi, Pearson, & Feder, 2009). Recent studies have shown that students engaged in engineering design activities do not implicitly learn science concepts at all (Blumenfeld et al., 1991; McRobbie, Stein, & Ginns, 2000; Silk, Schunn, & Cary, 2007). While it does help students integrate abstract thinking into concrete applications (Roth, 1996, 2001) and learn a variety of concepts set into context, such as problem-solving skills (Roth, 1996), teachers must balance managing the design challenge with helping students understand the science concepts related to the design (McRobbie et al., 2000). The National Academy of Engineering and the National Research Council explicitly recommend research efforts to determine how science inquiry can be merged with engineering design curricula at the K-12 level so that ‘the most important concepts, skills, and habits of mind in science and mathematics … can be taught effectively using an engineering design approach’ (Katehi et al., 2009, p. 8).

Theoretical Frameworks

The central features which define this research are: problem-solving through authentic tasks, determining and addressing alternative conceptions, working within social groups, creating tangible artefacts which are meant to represent knowledge (Sadler, Coyle, & Schwartz, 2000), and sideline guidance by a more knowledgeable person—the teacher. These features map neatly to the social constructivism theoretical framework and to conceptual change theory.

The social constructivist framework stresses that students play an active role in their own learning, and should work together to solve problems while discussing and debating. The role of the teacher is to determine students’ alternative conceptions, provide concrete sense-making activities which address those conceptions, and facilitate interpretive discussions about the subject. The teacher is a facilitator of learning, and takes an active role in interacting with students to find out what they know and what they are thinking. Knowledge is constructed by the individual, but mediated through social interactions with peers and the teacher in the classroom (Palinscar, 1998; Tobin & Tippins, 1993).

Papert (1980) described artefacts as ‘objects to think with’ because they help bring abstract concepts into the concrete and tangible realms. When artefacts are shared and critiqued by others, students use them to reflect on what they know (Krajcik & Czerniak, 2007). Designed and created artefacts can free up mental resources for developing more complex ideas (Roth, 2001). In design-based science activities, the artefact is the central focus where every component of the designed device is supposed to serve a real purpose and reflect some scientific knowledge. Additionally, researchers have demonstrated that when students have greater interest in what they are learning, they will process information at deeper levels (Brophy, 1998; Hidi, 1990; Schiefele, 1991). Problem-solving and design tasks that relate to students’ lives should be the catalyst to increase student interest and promote deeper conceptual knowledge.

Although constructivism has had a major influence on science curricula and pedagogy for the past 30 years (Fensham, 1992; Matthews, 1997), critics of constructivist instruction claim that novice learners perform better with direct, guided instruction. Furthermore, critics assert that minimally guided, inquiry-based teaching places too heavy a cognitive load on a limited working memory (Kirschner, Sweller, & Clark, 2006). However, in the present investigation, as students were constructing their understandings through concrete, relevant activities, interpretive discussions played a key role both within groups, between groups, and with the teacher as a whole class. Therefore, the teaching philosophy in this study can be seen as guided constructivism (Green, Piel, & Flowers, 2008). The teacher as ‘guide on the side' (King, 1993) helped facilitate learning, and students were not left to their own devices to rediscover the laws of thermodynamics.

For the past three decades, research has demonstrated that people have deeply rooted beliefs, or alternative conceptions, about how the world works, and these beliefs commonly contrast with current scientific views (Duit & Treagust, 2003). The conceptions are creative and useful to a child as he or she navigates the practical world, and must be respected as such, but teachers need to be aware of their students' alternative conceptions and focus on helping their students restructure them (Brown, 1992; Clement, 1993). Alternative conceptions are highly resistant to change as people are usually very reluctant to discard their long-held beliefs.

The conceptual change model informs educators about how to best address students' alternative conceptions in science. The first conceptual change model was proposed by Posner et al. (1982), and later the model was revised by Hewson and Hewson (1983), Vosniadou (1994, 1999, 2002) and others. Strike and Posner (1992) describe that learning does not necessarily imply conceptual change, that in order for one conception to change an entire ecology of conceptions must change with it, and that young learners may not necessarily hold alternative conceptions but they might hold images or intuitions about the way the world works. Alternative conceptions may actually be generated by students in school to solve problems, reorganize ideas, and make sense of new information (Stafylidou & Vosniadou, 2004). However, once a student's conceptual ecology is determined, appropriate experiences need to be introduced to target the alternative conceptions and introduce scientific ones (Vosniadou, 1994).

One way to address alternative conceptions is by providing students with concrete, understandable, believable, explicit, and visual examples (Brown, 1992). Another effective method is through the use of experimental lessons and demonstrations which can serve as bridging analogies (Clement, 1993). Vosniadou (1994) recommends problem-solving and verbal explanations. In this study, examples, lessons and demonstrations, shared discourse, and engineering design problems were used to try and help students develop scientific conceptions of heat transfer and thermal energy.

Operational Definitions

The terms heat, energy, and thermal energy are often used inconsistently. Heat is the transfer of thermal energy between two systems at different temperatures. Thermal energy, often called heat energy, is a property of a body or system related to its temperature. It is the portion of internal energy that can be transferred due to temperature differences. A body or system has other forms of internal energy such as chemical or nuclear energy, but these do not transfer when subjected to a temperature change (Çengel & Boles, 2006). Heat and heat transfer actually have the same meaning because heat is the *transfer* of thermal energy. Heat is not simply a quantity of energy; it is a quantity of thermal energy transferring (Giancoli, 1991). For the purposes of educating middle-school students about heat and thermal energy, abstract atomic and molecular models are avoided in favour of concrete examples students can relate to their everyday lives (Cajas, 1999; Lewis & Linn, 1994).

Purpose

The purpose of this study is to better understand how middle-school students can learn significant science concepts at a deep conceptual level through an engineering design challenge that encourages the application of scientific understandings. This study explored how engineering design activities could be used to target standards-based science concepts and promote conceptual change. Three treatment variations were presented in order to compare engineering design-based pedagogy to more traditional pedagogy. One treatment was the teacher's typical instruction without engineering design. One treatment was an engineering design curriculum with demonstrations embedded to target students' alternative conceptions, and one treatment was the same engineering design curriculum without targeting alternative conceptions. Without explicitly addressing alternative conceptions, it was hypothesized that engineering design alone would not be enough to promote conceptual change in science. The major research questions were:

(1) What are students' conceptions about thermal energy and heat transfer before instruction?
(2) How do students' conceptions about thermal energy and heat transfer change after instruction in each of the three treatments?
(3) How do the three instructional approaches compare in promoting conceptual change?

Methods

This mixed-methods study examined one teacher and her three classes of eighth-grade students ($n = 71$) in a suburban public school in the Mid-Atlantic region of the USA. Students worked in small collaborative groups on activities centred on the science of thermal energy and heat transfer. The three intact classes in this study were statistically equivalent in terms of their state math and reading scores from seventh grade. Since students were already assigned to their classes, they could not be randomized to one of the three treatments; therefore a coin toss was used to determine which of the classes would receive each treatment. The engineering treatments in this study used the design-based science curriculum called *Save the Penguins* (STP) which was developed at the University of Virginia through the Virginia Middle School Engineering Education Initiative. Initiative (Schnittka, Bell, & Richards, 2010). In the *Save the Penguins* curriculum, students are challenged to create a dwelling that reduces heat transfer in order to keep a penguin-shaped ice cube from melting. Students work in peer-mediated groups and play an active role in their learning as they solve problems and cooperate on the design and testing of the device. Variations of this curriculum were used with two of the classes. The first class served as the control group.

Participants

The first class (always referred to as the Control class) consisted of 27 students: 17 male and 10 female. All students were Caucasian. The second class (always referred to in this paper as the *STP*+ class) consisted of 23 students: 12 male and 11 female. Seventeen students were Caucasian, two boys and one girl were of Asian ethnicity, one girl was of South Asian ethnicity, one boy was African-American, and one girl was African-American. This was the most ethnically diverse class in the study. The third class (hereby referred to in this paper as the STP class) consisted of 21 students: 9 male and 12 female. All students were Caucasian except for one female of Hispanic ethnicity and one male of South Asian ethnicity. The teacher in this study had four years of full-time middle-school science teaching experience. She was working part-time on a master's degree in educational leadership at the time of this study, had experience as a science department chair, and was certified to teach middle-school science in three states. She was an enthusiastic teacher, interested in cooperative learning, student motivation, integrating life and physical science instruction, and had experience using design as an instrument to facilitate teaching physical science concepts.

Site

This study took place at Montebello Middle School,[1] a rural public school in a Mid-Atlantic state. It is the largest middle school in a county with approximately 100,000 citizens. Data published for the 2006 school year[2] reported that with 747 students, 89.6% were Caucasian, 4.3% were African-American, less than 2% were Asian-American, and 2.1% were of Hispanic ethnicity. During the 2006 school year, 10.6% of students were eligible for free or reduced lunch. Montebello Middle School is located in the rural countryside between a medium-sized city and a small county town. Its students feed from four rural elementary schools; two of these schools are considered to be in affluent areas of the county while two are not.

Treatments

Students in all three classes were taught about thermal energy and heat transfer with the same learning objectives, the same homework assignments and journal prompts, and the same end-of-unit test. The unit took six 80-minute class periods to complete. In order to insure treatment fidelity and equivalent opportunities to learn the science concepts, all three classes were observed daily throughout the study and observations were discussed with the teacher daily. Two major differences existed between classes—the design activity and the targeted demonstrations. Students in the Control class were taught through the teacher's typical instruction, an inquiry-based, active-learning curriculum the teacher used the previous year. Students in the *STP*+ class were taught science through engineering design with the *Save the Penguins* curriculum, but they also experienced five targeted demonstrations developed for this study.

Day	STP class	Control class	*STP*+ class
1	Discuss caloric, heat, heat transfer. PowerPoint about engineering. Discussion of engineering.	Discuss caloric, heat, heat transfer. PowerPoint on thermal energy. Discuss methods of heat transfer and examples. Students make books on heat transfer. Students watch video on heat.	Discuss caloric, heat, heat transfer. PowerPoint about engineering. Discussion of engineering. Cans demonstration.
2	Discuss heat and temperature. Balloon demonstration. Demo with beakers of hot and ice water. Demo of food colouring in different temperatures of water. Students make storyboards about heat transfer.	Discuss heat and temperature. Balloon demonstration. Demo with beakers of hot and ice water. Demo of food colouring in different temperatures of water. Students conduct a phase change lab in groups.	Discuss heat and temperature. Discuss cans demonstration. Trays demonstration. Spoons demonstration. Students make storyboards about heat transfer.
3	Discuss how a thermos works. Watch video on heat. Introduce design challenge. Test materials.	Discuss how a thermos works. Computer lab research time on building materials or clothing that prevents heat transfer.	Discuss how a thermos works. House demonstration. Mylar demonstration. Introduce design challenge. Test materials.
4	Discuss insulators and metals. Test materials and share results.	Discuss insulators and metals. Students work on posters about their research.	Discuss insulators and metals. Test materials and share results.
5	Students build houses and test them.	Students work on posters. Students complete a computer simulation activity on conduction.	Students builds houses and test them.
6	Students discuss designs and re-build and re-test. Students take posttests.	Students work on vocabulary for end of unit preparation. Students take posttests.	Students discuss designs and re-build and re-test. Students take posttests.

Figure 1. Treatments and activities

Students in the STP class were taught science through engineering design with the *Save the Penguins* curriculum, but without five demonstrations that specifically targeted students' alternative conceptions about thermal energy and heat transfer. Figure 1 illustrates the three treatment classes and activities that were conducted during the six class periods.

Targeted Demonstrations

Five demonstrations were developed for the *STP*+ class, based on the alternative conceptions identified in their heat transfer evaluation (HTE) pre-test results. In the first of these targeted demonstrations, students predicted which material, wrapped around a can of soda, would keep it cold the longest. This demonstration targeted students' alternative conceptions that aluminium foil 'traps coldness' and wool socks warm things. Another demonstration had students observe ice cubes placed in plastic and metal spoons they held and predict which one stay frozen longest. This demonstration targeted students' alternative conception that metals are naturally colder than plastics, and would therefore keep an ice cube frozen longer. Other demonstrations involved a cardboard house with a black painted roof under a heat lamp with temperature probes in the attic and first floor spaces. The house was heated, temperatures were measured, and students predicted what would happen when the house was flipped upside down. This demonstration targeted student's alternative conception that heat is a substance that rises, and helped students visualize the hot air rising, not 'heat'. In a final demonstration, aluminized Mylar material was draped over a student's hand under a heat lamp, and the student made observations and inferences. This demonstration targeted students' alternative conception that shiny objects 'absorb heat'. Together, these demonstrations took approximately one class period.

Typical Demonstrations

Students in the Control class and the STP class participated in demonstrations which the teacher typically used to illustrate convection, conduction, radiation, and thermal energy. She showed students food colouring in three different temperatures of water and had them explain the differences. She had students measure and graph the temperature of an ice bath as it heated on a hot plate to boiling. She placed balloons in the freezer and left some at room temperature for students to observe and make inferences about. She showed a Bill Nye (1996) video with demonstrations about heat and temperature that could not be performed in the classroom. In one demonstration, Nye tried to melt a large ice sculpture with a single burning match. He tried to explain that the ice sculpture needed more energy to melt than the match had to transfer. He said:

> Which has more heat energy, this hot burning match, or this beautiful ice sculpture of science? The match is hot and the sculpture is cold. Well, they're both made of molecules, but which has more molecules? The ice sculpture. A lot more molecules. So although they're much colder than the match, they actually have more heat energy. More molecules, more heat energy.

Nye also demonstrated that brownies in a glass pan do not need to cook as long as brownies in a metal pan because the metal pan reflects the radiation while the glass pan is transparent to it. These typical demonstrations illustrated methods of heat transfer, but did not specifically target any particular alternative conceptions students might have about heat transfer and thermal energy.

Engineering Design Challenge

The *Save the Penguins* engineering design challenge presented to the STP and *STP+* classes began with a scientific inquiry as students tested materials with which to build a dwelling for the penguin-shaped ice cube to keep it from melting in a test oven. Students were provided with materials such as felt, foam, cotton balls, paper, shiny Mylar, and aluminium foil to test for their effectiveness at preventing some form of heat transfer. Students compared materials under a shop light mounted to a ring stand, shining on a black surface. Students had access to temperature probes and timers to fairly test samples under the light or on the hot black surface. As students explored the materials, they began to formulate ideas about how to build their dwelling for the ice cube so that the least amount of ice melted. All materials were priced and 'sold' to students who worked within the constraint of a budget. They were able to purchase materials after testing them, discussing the results, and deciding which ones were better building materials.

Testing the Design

Students had the opportunity to elaborate on the knowledge they gained from the demonstrations, discussions, and testing when they got out their scissors, tape and glue, and took on the role of engineer as they purchased materials, designed, and built their dwellings. Students conducted further testing, discussed results with other groups, and received support for their ideas from the teacher and peers. The carefully created and frozen 10 g ice penguins were placed inside the individual dwellings and then simultaneously placed in the oven and subjected to 20 minutes of intense radiation, convection, and conduction (see Figure 2).

Figure 2. Dwellings in the oven

The oven was a large plastic storage bin lined with aluminium foil on four sides and spray-painted black on the bottom with three 150 W shop lights shining inside so that all three forms of heat transfer could occur. Houses placed in this pre-heated oven experienced conduction with and radiation from the black floor, radiation from all sides, and convection as cooler air sank and warmer air rose off the black bottom. After testing, students discussed which design features were best at preventing conduction with the black oven bottom. Which design features were best at preventing radiation from the heat lamp from penetrating the dwellings? Which design features were best at preventing the convection of hot air moving? The students discussed and decided. They analysed the results, and then went back to the drawing board to make revisions and improvements.

Students were able to use their communally shared results and ideas to make revisions that prevented more melting. Each group of students was a winner if their revised design was better than their first one. Just as engineers continually work together in an iterative process to make things better, the middle-school engineers did the same.

Data Collection and Analysis

A variety of data sources were used to determine how students were learning about science and engineering in the three classes. These data sources included daily observations of all classes, formal interviews with a subset of students prior to and after instruction, formal and informal interviews with the teacher, and all participant-created artefacts.

Observations

Daily classroom observations of all three treatments were made by the first author. They were videotaped from the back of the room with an on-board microphone and a wireless lavaliere microphone on the teacher. All videos were transcribed for analysis. A total of 18 observations of 80 minutes each were made during the intervention, and a total of 15 observations of 80 minutes each were made prior to the intervention in order to familiarize the students with the presence of an observer and video camera. Observations were a primary source of data for characterizing how the students interacted with the different curricula, interacted with the teacher, and interacted with each other.

Pre- and Post-Test

All participants completed a 12-item multiple choice HTE pre-test two weeks prior to instruction, and as a post-test immediately following the intervention. While the repetition of this test four weeks later may be seen as a threat to internal validity, all participants in all three treatment groups were administered the same test pre and post on the same days, so any gains due to repeated testing can be assumed to be equally distributed. Although the unit of analysis was at the class level, statistical analyses were used with the pre-test as the covariate following the advice of Campbell and Stanley (1963) for quasi-experimental designs in education.

The HTE was informed in part by questions from the 26-item thermal concept evaluation (TCE) designed for high school students (Yeo & Zadnik, 2001). Five test items were chosen from the TCE and modified slightly while seven test items were researcher created based on research-based alternative conceptions (Driver et al., 1994; Erickson & Tiberghien, 1985; Lewis & Linn, 1994). The purpose of administering this instrument was to identify alternative conceptions students possessed about heat transfer and thermal energy, and compare differences between classes and between times it was administered. Prior to this study, the HTE instrument underwent extensive evaluation of reliability and face, content, and construct validity and was found to be both reliable and valid for this study (Schnittka, 2009). Face and content validity were ascertained by a panel of eight experts in the field of physical science education who reviewed the instrument to determine if it sufficiently tested the content of heat transfer and the objectives of the curricula. The assessment was modified according to the panel's suggestions, and further rounds of review and modification took place until 100% agreement was attained for wording and inclusion of each test item. Linear regression was used in a test–retest study to determine that the correlation coefficient was $R = 0.71$. The primary alternative conceptions addressed in the HTE were:

(1) Cold moves from cold places to warmer places.
(2) Insulators keep cold out and/or generate heat.
(3) Lighter coloured clothes keep you cooler because they let more air in.
(4) Metals attract heat.
(5) Heat rises.
(6) Aluminium foil is a good insulator for cold things.
(7) Heat moves because it builds up in once place which cannot hold it.
(8) Metals are naturally colder than non-metals.
(9) Light coloured or shiny objects absorb radiation.

Five of the 12 questions addressed conduction, three addressed insulation, three addressed radiation, two addressed convection, and three addressed the directionality of heat transfer. Some items addressed two constructs.

Interviews

A representative subset of students from each class was interviewed prior to and after the interventions. Eleven students in the *STP*+ class, eight students from the STP class, and 10 students from the Control class volunteered for interviews. In order to make sure that the interviewed students represented each class as a whole, their pre-test scores on the HTE were compared. Means were 4.1 out of 12 for the *STP*+ students, 4.38 for the STP students, and 4.9 for the Control students. Each sample equally represented a distribution of students who scored high, middle, and low on the HTE pre-test. Interviewed student pre-test scores on the HTE were statistically equivalent (p = 0.715, effect size r = 0.11). The teacher was formally interviewed prior to the interventions, informally throughout the duration of the study, and formally at the conclusion of the study. All interviews were audiotaped and transcribed for analysis.

Additionally, designed artefacts, homework assignments, and class-work assignments were analyzed for additional information about students' learning, and were used as prompts during interviews.

Results

Pre-Instruction Results

Prior to instruction, participants in all three treatment groups had similar conceptions about heat transfer and thermal energy. The *STP*+ class mean was 4.09 out of 12 possible points, the STP class mean was 4.33, and the Control class mean was 4.63. Classes were statistically equivalent on the HTE pre-test (p = 0.601) with an effect size r = 0.09. These scores were slightly better than chance. See Figure 3 for box plots (also called box and whisker plots) representing the range of pre-test scores for each class. Box plots illustrate the median, quartiles, and range of data. The box extends to the 25th and 75th quartiles with the dark line representing the median. The whiskers extend to the highest and lowest reasonable values with the small circles representing outliers. In both the STP and Control classes, the median value is the same as the 25th percentile value due to outliers.

Prior to the interventions, students were familiar with everyday experiences with heat and temperature, such as body heat. They believed 'heat' to be something hot, the opposite of cold. Few students understood heat to be the transfer of thermal energy. Students often articulated that metals absorbed cold, imagining cold to be some sort of substance that flowed, getting trapped and absorbed. Jim was typical in stating that, 'So if you like, have a cup of water you put in the freezer, then the cold air from the freezer gets the water and makes it into an ice cube' (Jim, Control class, entrance interview).

These conceptions about heat and temperature seemed to come from students' personal experiences with staying warm, getting burned, and feeling cold in their everyday lives. In order to make some sense of their world, they developed their own theories, their own alternative conceptions. On average, there were twice as many alternative conceptions expressed by students in all classes as there were scientific conceptions. The most common alternative conceptions expressed were:

(1) cold transfers from cold to warm;
(2) insulators generate heat;
(3) insulators are warm, metals are cold;
(4) insulators keep cold from transferring;
(5) metals trap or absorb cold;
(6) heat is always warm or hot;

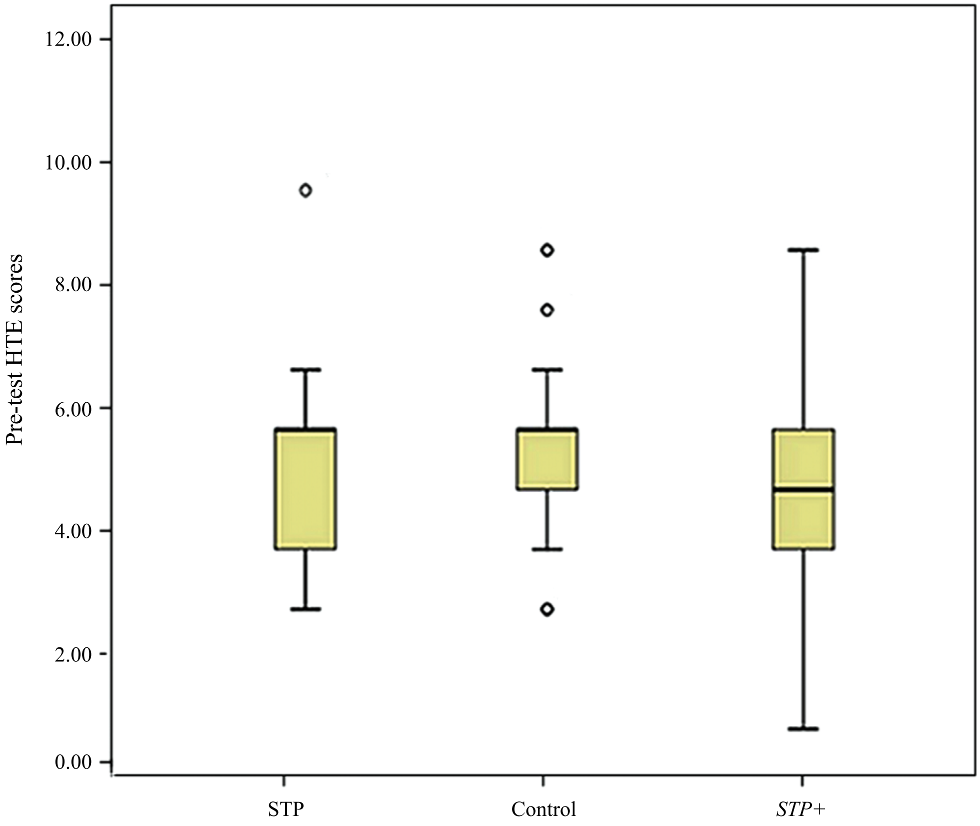

Figure 3. Pre-test scores for each class

(7) heat and temperature are equivalent;
(8) heat always rises; and
(9) dark objects attract heat.

Students articulated these alternative conceptions with nearly the same frequency in all three classes. When tabulated from transcriptions of entrance interviews, there were 40 instances expressed by students in the Control class, 39 instances of any one of these conceptions expressed by students in the *STP*+ class, and 41 instances expressed by students in the STP class. Students expressed these conceptions by stating: 'Like if it's snowing, it's not going to have heat, or if you are underground it's cooler because heat rises up' (Sarah, STP class, entrance interview) or 'So if you like, have a cup of water you put in the freezer, then the cold air from the freezer gets the water and makes it into an ice cube' (Jim, Control class, entrance interview). Sarah, a student in the STP class illustrated concepts 2 and 3 in the following discussion:

Researcher:	So if you put a sweater on a counter, would the counter get warm or would the sweater get warm by itself?

> Sarah (STP class, entrance interview): The countertop would be warmer.
> Researcher: Would the sweater itself generate heat?
> Sarah: The bottom of the sweater, the one laying on the countertop would.

During-Instruction Results

Based on observations, interviews, and data collection, students acquired knowledge about heat transfer and thermal energy through different activities, and to different degrees during the intervention. Post-tests and exit interviews were used after the intervention to help determine how students' conceptions changed depending upon which intervention they received.

The following excerpt is from day four of the unit in the STP class as students and teacher discussed materials available for purchase. Since students did not have the targeted demonstrations to refer to, they were using information from their materials testing to make design decisions:

> Teacher: Next thing, you're going to have to think about building your igloo. You have to think about radiation coming from where?
> Students: The lamps.
> Teacher: We're going to have the heat lamps turned on ahead of time. Is there conduction? Is there convection? Yep. There are three things you have to think about. What was a good thing to reflect radiation?
> Reggie: Mylar and aluminium foil.
> Teacher: What about to insulate?
> Kate: Bubble wrap.

Students demonstrated a basic understanding of radiation and insulation. As students in this class were re-designing their dwellings on Day 6 of the intervention, they were still making use of the knowledge they gained from the materials testing. The following excerpt is from a discussion that one student group in the STP class was having while trying to re-design their dwelling for the second test in the hot oven. They had determined they would use paper as a building material, and were debating which colour to use. They had previously tested sample pieces of coloured paper under shop lights:

> Margaret: That's a dark colour, it will attract heat.
> Daniel: I think white paper.
> Margaret: Yeah, white paper.
> Reggie: We need to do something to give it more shade.
> Daniel: I don't think we have enough materials to build shade.

The students were thinking about the materials in terms of which ones were affordable, within their given budget to purchase supplies, which ones would provide shade from the radiation, which ones would reflect radiation, and which ones were good insulators. They made creative use of the less-expensive materials available to them; they discussed air as a good insulator, used a reflective material on the bottom of the dwelling to reflect radiation from the black floor, used light colors instead of dark ones, and reduced conduction by raising the dwelling off the floor.

Students in the STP class were not using many scientific terms in their group discussions as they designed and built the dwellings even though they were assigned the same textbook readings for homework as students in the other classes. Their class activities were mostly in peer groups, and their knowledge was primarily socially constructed in those groups.

Students in the Control class learnt in social groups as well during their activities, but these activities were less open-ended and conversations were usually about procedures and results with little debate and scientific discussion. The conversations in the Control class were more authoritative than dialogistic, and whereas students in the STP class were working together to solve problems and use the concepts of heat transfer and thermal energy in a design, students in the Control class were learning terms and definitions and following the directions of guided inquiry activities.

Students in the *STP+* class performed the same tests on materials, and constructed the same types of dwellings for penguin-shaped ice cubes as students in the STP class. However, they faced cognitive dissonance when shown five targeted demonstrations. They then referred back to these demonstrations in their discussions. Students in the *STP+* class made the most significant positive changes in scientific understandings during the intervention compared to students in the Control class and the STP class. When students in the *STP+* class began designing their penguin dwelling, students were able to apply correct knowledge about metals to the design of the dwelling by referring back to the targeted demonstrations. Students who did not have the complete *STP+* curriculum held onto the idea that metals kept in coldness, trapped cold, were colder than other materials, attracted and absorbed cold. Very few students in the *STP+* class had these conceptions.

Many students articulated that hot air rises during the interventions, however the *STP+* class made the most gains in understanding that it is hot air, not ‘heat’ as a substance that typically rises. However, there was discussion amongst the students in both design classes about how hot air would be rising off the black bottom of the test oven, and how they had to seal their dwelling from this hot air. Students in the *STP+* class also articulated with greater frequency how conductors can take thermal energy away from your body. This is most likely due to the demonstration with the spoons and the trays, and the discussion afterwards about how ‘cold’ does not move into the hand, but thermal energy from the hand moves into the spoon and melts the ice cube. However, students in all classes had experiences with a lab or demonstrations involving ice melting. A group of students in the STP class realized that simply touching and placing their ice cube in the dwelling would cause some of it to melt, and decided to pick it up with bubble wrap to prevent thermal energy from transferring to the ice cube.

Students made positive gains in their understandings of insulation during all three interventions, but especially in the *STP+* class. Students in the *STP+* class had many scientific conceptions about insulation, whereas the other classes had fewer scientific conceptions. The statements that wood is an insulator, that a vacuum is a better insulator than air, that air is a good insulator, and that plastic is a good insulator were made by students in the *STP+* class more frequently than students in the other two classes. If this is due to their experiences with insulating materials in the construction of the penguin dwellings, why was there a difference between the two engineering design classes? Perhaps the demonstration with the cans covered in different materials made a lasting impact that helped them understand the insulating properties of the building materials better.

Post-Instruction Results

Figure 4 illustrates the median, quartiles, and range of scores on the HTE post-tests for each class.

In all three classes, the gains from pre- to post-test on the HTE were statistically significant ($p < 0.001$). However, an ANCOVA using the pre-test score as the covariate demonstrated that the classes were not statistically equivalent in terms of their change in heat transfer knowledge across time $F(2, 67) = 6.549$, $p = 0.003$, with an effect size of $r = 0.29$. There was a significant difference between the *STP+* class scores and both the STP class scores and the Control class scores. There was no

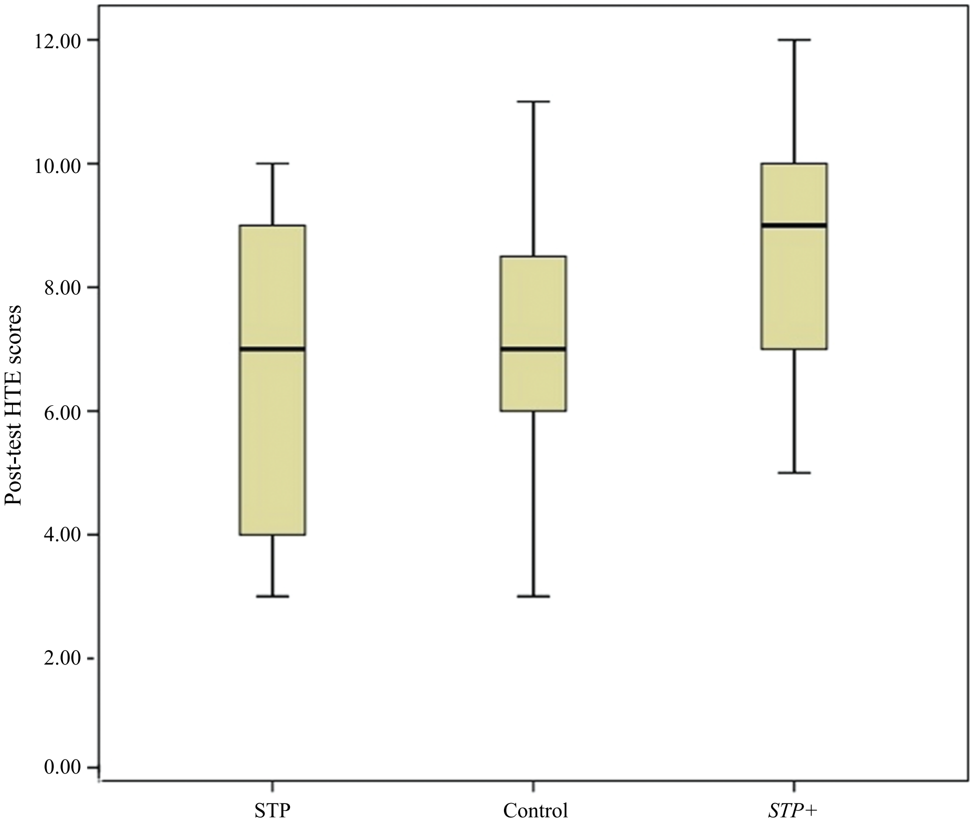

Figure 4. Post-test scores for each class

significant difference between the STP class scores and the Control class scores. See Table 1 for means. Figure 5 illustrates the interaction between classes on the HTE score means.

Based upon HTE post-tests and exit interviews, students in the *STP*+ class made more gains in understanding heat transfer and thermal energy than students in other classes. Students in the *STP*+ class had a better understanding that heat can be transferred from room temperature or even cold objects as long as the heat is moving

Table 1. Pre- and post-test means and standard deviations on the HTE

	Pre-test	Post-test
STP class (*n* = 21)	4.33 (*SD* = 1.83)	6.43 (*SD* = 2.52)
Control class (*n* = 27)	4.63 (*SD* = 1.64)	7.19 (*SD* = 1.84)
STP+ class (*n* = 23)	4.09 (*SD* = 1.81)	8.22 (*SD* = 1.94)

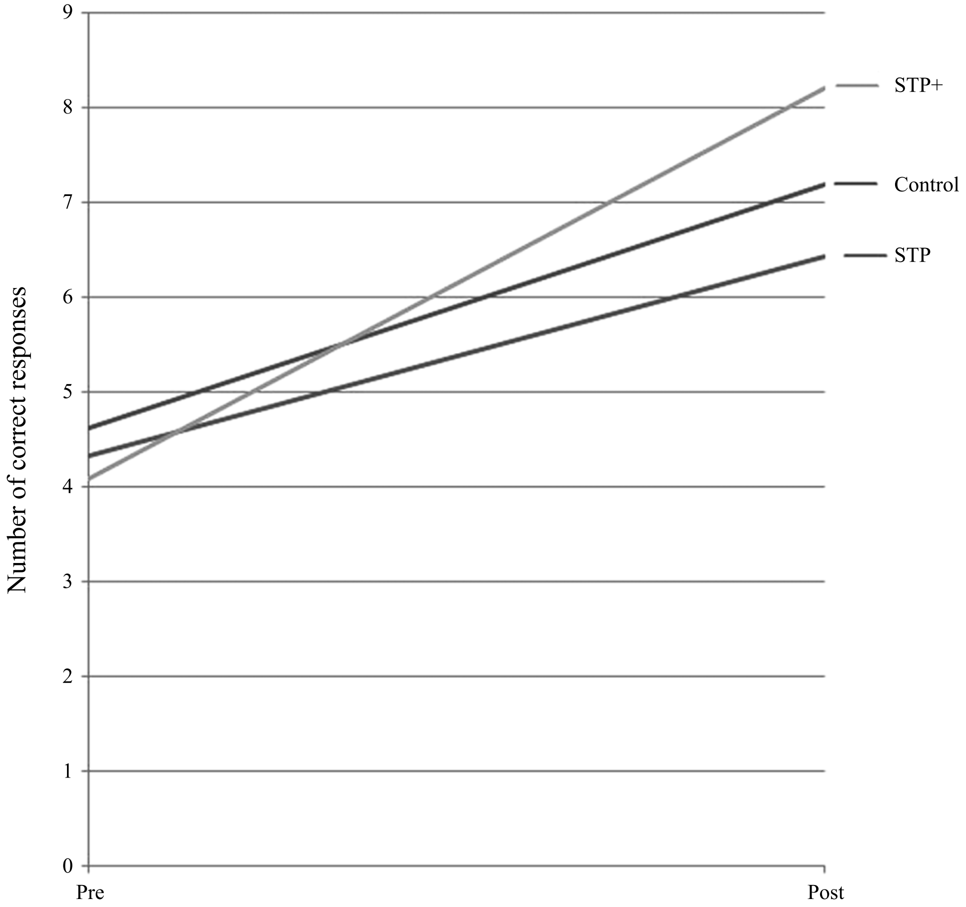

Figure 5. Interaction between classes pre to post

to an area with a lower temperature. Fewer students in the *STP+* class expressed alternative conceptions, such as 'heat rises' and 'cold transfers'. Students in the *STP+* class understood insulators and conductors better. They were also able to better apply their knowledge to new situations.

When compared with the list of alternative conceptions that students articulated during entrance interviews, each class made positive gains in reducing the number of alternative conceptions held about heat and thermal energy. Students in the *STP+* class articulated 12 alternative conceptions during interviews after the intervention, students in the Control class articulated 13, while students in the STP class articulated 21, the greatest number of alternative conceptions after intervention.

Exit interviews were conducted with a representative sample of 10 students from each class, primarily the same students who had participated in entrance interviews. Students in the Control class held approximately the same number of alternative conceptions as students in the STP class after instruction. The following quote is typical of students interviewed in the Control class. Prior to instruction, Paul, like most other students in the study, had typical alternative conceptions about freezing water. In his entrance interview, he described a box in the freezer that keeps things cold. He said, 'I thought the water would absorb the coldness from the air because of the little weird thermometer or temperature thing'. After instruction, Paul's conception did not change. He said:

> The water absorbs the coldness from the freezer because the freezer has like a fan in it blowing cold, really cold air and I would think that the water would absorb that and it would turn to ice (Paul, exit interview, Control class).

Prior to instruction, Diana, a student in the *STP+* class was not able to correctly answer the question, 'Why is it cold on the countertop underneath a can of cold soda'? Her response illustrated the alternative conceptions that 'cold transfers' and 'temperature transfers':

> Researcher: Why is it cold on the countertop underneath a can of cold soda?
> Diana: Because the soda is cold and it goes through the aluminium.
> Researcher: What goes through the aluminium?
> Diana: The temperature. And then it transfers to the counter because I guess, yeah, it transfers to the counter. (Diana, entrance interview, *STP+* class)

After instruction, Diana's conceptual understanding shifted to a more scientific one. She correctly described the directionality of heat transfer:

> The countertop was warmer than the soda and so the heat from the countertop travelled into the soda and made the soda warmer but when a substance transfers heat to the colder substance, that substance loses heat so the countertop became colder. (Diana, exit interview, *STP+* class)

Sakura, a student in the *STP+* class was typical of those interviewed in her group, in correctly stating that energy leaves the water in order for it to freeze. Prior to instruction, Sakura was very confused about why water freezes. She said the water absorbs 'the coldness from the freezer' because the 'air in the freezer is very cold' and that the water 'adjusts to the air and becomes the same temperature'. After instruction, Sakura had a more scientific conception of heat and energy. She said:

> There's no such thing as coldness so the water can't absorb the coldness. The air, it takes the heat out of the water. It makes the water have less energy so it becomes a solid. (Sakura, exit interview, *STP+* class)

Students in the STP class did not modify their conception that cold is a substance that travels as much as students in the *STP+* class did. Only 52% of students in the STP class had a scientific conception of 'cold' after instruction whereas 72% of students in the *STP+* class had a scientific conception. Prior to instruction, Jenny was unclear about why water freezes. She said:

> Whenever I open the freezer door, I see like smoke or coldness when I stick my hand in and sometimes I feel my hand actually get cold because of it, so I think that the water most likely, it feels the coldness of the whole freezer and then it just kind of freezes itself, I guess. (Jenny, entrance interview, STP class)

After instruction, Jenny was still unclear about why water freezes. She said:

> I don't know if it's right, but I think when you open the freezer and there's all that cold air, I still think that the ice just like, it's cause it's so cold, that it just absorbs all of that coldness. I just think that. I don't think I'll ever think differently. (Jenny, exit interview, STP class)

Summary of Results

Students in the *STP+* class were the highest performing after the unit concluded. Not only did they outperform students in the other two classes on the HTE, they stated the fewest number of alternative conceptions about heat transfer during their exit interviews. As evidenced by statements made in their exit interviews, their direct experiences applying their knowledge to the design challenge allowed them to make connections and understand the concepts at a more sophisticated level. Their conceptual understanding, which was aided by the design activity and a set of five targeted demonstrations, allowed them to make better sense of the science and apply

Figure 6. Sample dwelling designs

it more fully towards the engineering design task. Ten of the 12 penguin dwellings in the *STP+* class performed at a satisfactory level (retaining half the mass of the ice cube) whereas only seven of the 12 designs in the STP class performed at this level (see Figure 6 for sample dwelling designs). Perhaps increased understanding of heat and thermal energy allowed students in the *STP+* class to do a better job designing and constructing a device to prevent the transfer of thermal energy.

Discussion

The terms, 'heat' and 'temperature' are so very common in our everyday vocabulary that students often come to school at an early age with conceptions already formed about what these concepts mean (Albert, 1978; Clough & Driver, 1985; Erickson, 1979, 1980; Paik, Cho, & Go, 2007). Unfortunately, these conceptions are most often incorrect, and tend to mirror the eighteenth century caloric theory of heat. Students think of heat as a substance that flows or is made of 'heat particles', think of cold as the opposite of heat, and think of cold as something that flows as well. The scientific conceptions of heat, thermal energy, and temperature are often even misunderstood by senior level mechanical and chemical engineering students after specifically completing coursework in thermodynamics and heat transfer (Miller et al., 2006). If alternative conceptions are not addressed in school and if students do not experience ways to change or discard them, they will persist into adulthood, even in adults who have had explicit instruction in these areas of science (Lewis & Linn, 2003).

A confounding problem with understanding heat and temperature is that students use their senses to define these terms, and human senses can be deceiving. When students touch a metal tray and a plastic tray, they will state that the metal one not only *feels* colder, it *is* colder. They think of heat as always being hot, and use terms like 'body heat' and 'steaming hot' and 'icy cold' with a sense of knowing. Without instruction in kinetic theory, thermal energy, and heat transfer prior to their eight-grade year, they insist that when something feels cold to them, the 'coldness' is transferring *to* their bodies. Since birth people are surrounded by experiences with heat and temperature and thermal energy. This familiarity with the phenomenon naturally breeds alternative conceptions (Colburn, 2009).

Entrance interviews and pre-assessments were used in this study to determine students' alternative conceptions about heat transfer and thermal energy. After all students' alternative conceptions were elucidated, they were sorted and collapsed into a manageable set of distinct concepts:

(1) Cold transfers in order to make things cold or make them freeze.
(2) Wood and plastic are warmer than metal.
(3) Cold is a substance.
(4) Metals trap or absorb cold.
(5) Heat is something that is always warm or hot.
(6) Sweaters, blankets, and socks generate heat.

(7) Heat always rises.
(8) Dark objects *attract* heat.

All of these conceptions, or variations of them, were identified in previous studies of children ages 4–11 (Albert, 1978; Paik et al., 2007), ages 12–16 (Clough & Driver, 1985; Erickson, 1979, 1980), and even adults ages 19–45 (Lewis & Linn, 2003). Paik et al. (2007) discovered that the number of alternative conceptions children have about heat transfer may actually increase as they progress through school from age 4 to 11. They postulated that alternative conceptions may actually be formed at school during science classes.

The act of designing, conceptualizing, building, and testing a device which reduces heat transfer helped students modify alternative conceptions and create more scientific ones. However, when students' alternative conceptions about heat transfer and thermal energy were addressed up front prior to any design or construction of devices, students were able to take a different view of the design task and maximize its potential as a conduit through which to learn science. The design task and the science content appeared to be mutually supportive in the *STP+* class. Student groups who designed dwellings that preserved more ice, performed higher on the HTE post-test. Ironically, in the STP class, the better the student groups did at building a dwelling that kept the ice cube from melting, the worse they did on their HTE post-tests. It seems that the design and the science were competing instead of building on each other in the STP class, like a zero-sum game. These results have implications for how engineering design curriculum should be implemented in science classes.

Studies have shown that students engaged in design activities do not implicitly learn science concepts (Blumenfeld et al., 1991; McRobbie et al., 2000; Silk et al., 2007). Structure is required to bridge the gap between an engineering design problem and the science content which supports it (Puntambekar & Kolodner, 2005). In this study, demonstrations specifically designed to target common alternative conceptions were used to provide that structure for students in the *STP+* class. Five targeted demonstrations requiring a total of one class period facilitated student learning. Without addressing alternative conceptions, students doing engineering design did not increase their knowledge about heat transfer to the same degree as students in the other classes. These results support those found by other researchers (Penner, Lehrer, & Schauble, 1998; Puntambekar & Kolodner, 2005) who tested for science content gain, but found it lacking when an engineering design activity was used as the primary and sole vehicle for teaching.

Vosniadou (1994) describes enrichment as the 'simplest form of conceptual change' (p. 48). Enrichment takes place when new facts are added to students' conceptual frameworks. Revision of existing alternative conceptions, she describes, is a more difficult goal to achieve because new information conflicts with existing, deeply held framework theories that have existed for years. In this study, students in the *STP+* class made revisions to at least nine conceptions on the nature of heat and thermal energy. They made more revisions than students in the other two classes, and thus achieved greater conceptual change in their framework of thermodynamics.

Without a fourth equivalent classroom to serve as an additional treatment (typical instruction with targeted demonstrations), it was not possible to tease apart the effect of the design and the demonstrations on science conceptual knowledge. While students in the *STP*+ class performed better, students in the STP class performed statistically the same as students in the Control class on the HTE. Everything we know about conceptual change indicates that it is not likely that one class period of targeted demonstrations promoted lasting and durable conceptual change (Georghiades, 2000). Combined with an application in the form of a design task, perhaps the demonstrations had a more lasting effect. If the targeted demonstrations had replaced the typical ones in the Control class, would students have equalled or even surpassed the *STP*+ class? The researcher was careful to make sure that all three classes were exposed to interactive demonstrations for the same amount of time, but it is still unknown what role the targeted demonstrations played with regard to the engineering design activity. Perhaps the targeted demonstrations alone did not account for the success, but a combination of the demonstrations and the design activity allowed students to conceptualize heat transfer and thermal energy to a greater and more accurate degree, giving them an advantage over the STP class. The targeted demonstrations may have helped increase students' self-efficacy with the design task, and self-efficacy has been correlated with achievement (Weisgram & Bigler, 2006). Future research will address this question.

While the results of this study are not generalizable, it is unique when compared with all other studies of this type because it worked within the theoretical framework of social constructivism, used a statistically equivalent control group for comparison, examined science knowledge gains, used the same teacher for all groups, included interviews in all classes prior to and after the interventions to probe for deeper understandings, and utilized a mixed-methods approach to data collection and analysis. Because this study included so many robust design features, it was able to produce highly reliable insights about how engineering design can best be used in the middle-school science classroom for conceptual change.

The implication of these results is that some alternative conceptions will persist with an engineering design curriculum that does not explicitly address them. An engineering design intervention that addresses alternative conceptions is more successful in helping students learn science content at a deep conceptual level. Prior to instruction, students in all three classes expressed the same alternative conceptions with the same frequency. After instruction, students in the Control class had fewer scientific conceptions than students in the STP or *STP*+ class. Students in the *STP*+ class who were exposed to both the engineering design curriculum and the targeted demonstrations had half the alternative conceptions after instruction when compared with other students.

Implications from this study can inform teachers' use of engineering design activities in science classrooms. These implications are:

(1) Alternative conceptions will persist when not specifically addressed.
(2) Engineering design activities are not enough to promote deep conceptual change.
(3) A middle-school teacher with no formal engineering background can successfully implement an engineering design-based curriculum in a science class.

The teacher in this study stated in her entrance interview that prior to this intervention; she had never met an engineer. Her introduction to engineering occurred as she discussed and read through the curriculum with the first author (see Schnittka, 2010 for entire curriculum). She felt competent talking about engineering during the intervention, but admitted that it was not her strength. She used design activities in her physical science class the year before, but never explicitly tied these design activities to engineering. In previous studies which involved teachers who were new to engineering design-based curriculum, activities were couched in a 'design' framework, not an 'engineering' one (Hmelo, Holton, & Kolodner, 2000; McRobbie et al., 2000; Mehalik, Doppelt, & Schuun, 2008). 'Design' is a term that artists, architects, landscape designers, interior designers, fashion designers, and even hair-style designers use. It is a creative process, but one that does not necessarily rely on scientific or mathematical principles. While the activities in these previous studies *were* engineering design, calling them simply *design* activities may have helped teachers not feel intimidated by the curriculum. In the case of this study, the teacher felt prepared to stress the engineering aspects of what students were doing.

Limitations and Future Research

Every investigation has limitations that must be taken into consideration when interpreting the results and implications. In this study, limitations were identified which could have compromised the study in some way. However, the researcher always made overt attempts to mitigate these limitations. These limitations will be addressed in future research.

The sample of participants in this study consisted of high-achieving students of low diversity. Although it was ascertained that the three groups were statistically equivalent both in terms of their science and math scores from seventh-grade standardized tests, and they were also equivalent in terms of their knowledge of heat transfer prior to the intervention, the fact remains that the students in this study were all in academically advanced classes. They were primarily white and middle class. Would engineering design be as effective and well received in a more diverse or less academically oriented class? The National Assessment of Educational Progress (US Department of Education, 2000) reports from the past 30 years indicate that an achievement gap persists in science between students of different genders, ethnicities, and socioeconomic classes. Would this achievement gap narrow with less book-oriented activities and more active ones? Future research will investigate this question.

Middle and high school-aged students are commonly targeted for engineering design interventions (Jeffers, Safferman, & Safferman, 2004), as is the case in the present investigation. However, research indicates that elementary school students are capable of engineering design as well, and may benefit from the experience in terms of scientific and technological literacy (Brophy, Klein, Portsmore, & Rogers, 2008). Future research will take this approach to using engineering design in science contexts and apply it at the elementary level. Young children are adept at design and constructing; perhaps when targeted towards research-based alternative conceptions in science, engineering design activities will be just as effective at that age level.

Conclusion

Since 2001, more than 30 US states have incorporated engineering into their K-12 science or technology standards and science teachers are increasingly called upon to implement engineering design-based curricula (Miaoulis, 2009; Zinth, 2007). As more states move towards creating educational standards that include engineering concepts, the fact that a middle-school teacher with no formal engineering background successfully implemented an engineering design-based curriculum in a science class is encouraging. However, in order for engineering design activities to *add to* and not *detract from* deep conceptual understandings in science, care must be taken in how teachers enact the new standards they will be required to implement. The results of this study have strong implications for how teachers can truly and effectively use engineering design activities as a conduit for science teaching and learning.

Notes

1. All personal names and place names are pseudonyms.
2. Data reported in the latest annual progress report for the county.

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