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The Influence of Toy Design Activities on Middle School Students' Understanding of the Engineering Design Processes

Ninger Zhou[1] · Nielsen L. Pereira[1] · Tarun Thomas George[2] · Jeffrey Alperovich[2] · Joran Booth[2] · Senthil Chandrasegaran[2] · Jeffrey David Tew[3] · Devadatta M. Kulkarni[3] · Karthik Ramani[2]

Abstract The societal demand for inspiring and engaging science, technology, engineering, and mathematics (STEM) students and preparing our workforce for the emerging creative economy has necessitated developing students' self-efficacy and understanding of engineering design processes from as early as elementary school levels. Hands-on engineering design activities have shown the potential to promote middle school students' self-efficacy and understanding of engineering design processes. However, traditional classrooms often lack hands-on engineering design experiences, leaving students unprepared to solve real-world design problems. In this study, we introduce the framework of a toy design workshop and investigate the influence of the workshop activities on students' understanding of and self-efficacy beliefs in engineering design. Using a mixed method approach, we conducted quantitative analyses to show changes in students' engineering design self-efficacy and qualitative analyses to identify students' understanding of the engineering design processes. Findings show that among the 24 participants, there is a significant increase in students' self-efficacy beliefs after attending the workshop. We also identified major themes such as design goals and prototyping in students' understanding of engineering design processes. This research provides insights into the key elements of middle school students' engineering design learning and the benefits of engaging middle school students in hands-on toy design workshops.

✉ Ninger Zhou
znenancy@gmail.com

Nielsen L. Pereira
npereira@purdue.edu

Tarun Thomas George
tthomasg@purdue.edu

Jeffrey Alperovich
jalper@purdue.edu

Joran Booth
boothj@purdue.edu

Senthil Chandrasegaran
senthil.kumaran@gmail.com

Jeffrey David Tew
Jefferey.tew@tcs.com

Devadatta M. Kulkarni
Devadatta.Kulkarni@tcs.com

Karthik Ramani
ramani@purdue.edu

1 Department of Educational Studies, College of Education, Purdue University, West Lafayette, IN 47906, USA

2 School of Mechanical Engineering, College of Engineering, Purdue University, West Lafayette 47906, IN, USA

3 Tata Consultancy Services, Milford 45150, Ohio, USA

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Introduction

In response to the growing demand in the engineering education pipeline and the increasing interest in design thinking, educators have been searching for effective ways to broadening the participation in engineering and promoting students' engineering literacy in as early as elementary school levels (Carr et al. 2012). Among others, self-efficacy and the understanding of engineering design processes have been identified as influential factors for students' interest in engineering-related activities and career choices (Fantz et al. 2011). Given that self-efficacy beliefs can be effectively

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developed through mastery experiences, it is necessary to provide students with successful experiences of conducting engineering activities (Usher and Pajares 2008). However, there has been a lack of engineering activities in traditional classrooms, and most students will not have engineering-related mastery experiences until college (Hutchison et al. 2006; Moreno et al. 2016). As a result, students often have not developed self-efficacy beliefs in engineering design when they consider choosing a major for college or a career path (Lent et al. 2008). Therefore, in this study, we demonstrate the framework and activities of a toy design workshop, aimed at promoting middle school students' self-efficacy and understanding of engineering design processes. The research questions we address include (1) How does the toy design workshop influence students' self-efficacy in engineering design? (2) What is students' understanding of the engineering design process during the toy design workshop?

Background

Self-Efficacy in Engineering Design

Engineering design self-efficacy is the degree to which students believe that they can excel at tasks related to design and making (Carberry et al. 2010). According to social cognitive theory and previous research in science education, students' self-efficacy beliefs are influenced by mastery experiences, vicarious experiences, physiological states, and persuasion (Britner and Pajares 2006; Usher and Pajares 2008); the level of self-efficacy in a discipline can largely predict students' career choices and the willingness to persist through challenges (Bandura 1986). Thus, secondary school students who have limited mastery or vicarious experiences with design may develop relatively low levels of self-efficacy in engineering design and refrain from enrolling in engineering programs or pursuing engineering as a career. Even for those who are enrolled in engineering programs, low levels of self-efficacy beliefs in design would have an adverse effect on students' motivation and performance in engineering (Marra et al. 2009). Therefore, the goal of the current study was to identify ways to foster self-efficacy beliefs in engineering design for middle school students, so that they can develop positive attitudes towards processes integral to engineering and engineering-related career choices.

As previous literature has shown, self-efficacy concepts are content specific (Bandura 1986; Pajares 1992). In this section, although we draw on the rich body of research on STEM self-efficacy, in later sections, we still situate the discussion of this research in the context of engineering design. Existing research on engineering self-efficacy has mainly focused on college-level students. In a study by Hutchison et al. (2006), the first-year engineering students attributed their self-efficacy in an engineering course to a variety of reasons, ranging from previous exam/homework grades to enjoyment. Hutchison et al. identified nine types of reasons cited by the students as most influential to self-efficacy and associated these reasons with the four major sources of self-efficacy—mastery experiences, vicarious experiences, physiological states, and social persuasion (Bandura 1986). Hutchison et al. (2006) considered the learning of the material as exemplary of mastery experience (Hutchison et al. 2006), one of the most prominent sources of STEM self-efficacy beliefs (Lent et al. 1996), and considered teaming and seeking help as exemplary of vicarious experiences; getting comments from peers and instructors as exemplary of social persuasion; and enjoyment, interest, or frustration as exemplary of physiological states. This research suggests that in order to promote students' self-efficacy in engineering, it is necessary to provide experiences consistent with the major sources of self-efficacy (Hutchison et al. 2006). However, Hutchison et al. asked students to identify influential factors at the beginning of the course and did not show whether students improved in self-efficacy beliefs through obtaining related experiences.

In the limited literature on engineering self-efficacy at the secondary school level, researchers have examined the relationship between students' pre-collegiate experiences with self-efficacy beliefs (Fantz et al. 2011). Fantz et al. conducted a quasi-experimental study in which they surveyed students about self-efficacy in engineering classes and pre-collegiate experiences with engineering, such as whether or not the students had robotics as a hobby, received formal engineering curriculum in secondary school, or attended single/multi-day engineering workshops. The self-efficacy levels of students who had specific types of experiences were compared with those of the students who did not have the same experiences. Results showed that overall, pre-collegiate engineering experiences are associated with stronger self-efficacy. Students who had engineering-related hobbies and participated in formal engineering curriculum experiences in secondary schools reported significantly higher levels of self-efficacy than those who did not have such experiences. Such finding supports the need to provide engineering-related experiences for students prior to college. However, this study had students recall prior engineering-related experiences. It is necessary to also examine students' development in self-efficacy during their participation in engineering design activities.

Previous research has also investigated the influence of interventions focusing on engineering careers on middle school students' engineering self-efficacy. For instance, Plant et al. (2009) randomly assigned middle school students to either interact with computer characters who introduced the engineering career or have no computer interaction during class. Results showed that interacting with the computer characters increased students' self-efficacy in engineering.

However, this study implemented the computer characters to provide narrative accounts of engineering as a profession, rather than engaging students in hands-on activities related to engineering design.

In summary, previous research has mainly focused on associating students' prior experiences with self-efficacy in engineering. Limited research exists to show the influence of hands-on engineering design activities on students' engineering self-efficacy. Therefore, in this study, we address this gap by demonstrating an engineering design workshop centered on hands-on design activities and investigate if such experiences increase students' engineering design self-efficacy. Based on the sources of self-efficacy highlighted in social cognitive theory (Bandura et al. 2001; Schunk and Meece 2006), we provided engineering design experiences consistent with mastery experiences, through students' participation in design and making; vicarious experiences, through students' engagement in group hands-on activities; physiological states, through having students work on tasks that are enjoyable; and social persuasion, through instructors' constant verbal comments that acknowledge students' progress and improvement.

Understanding Engineering Design Processes

In alignment with the societal emphasis on nurturing next-generation makers and tinkerers, it is imperative to help students understand design concepts that are fundamental to the design process (Kolodner et al. 2003; Peppler 2013). Because design concepts have a broad spectrum, in this study, we choose to focus on those integral to the engineering design process, such as identifying problems, building prototypes, iteratively modifying prototypes, and communicating design solutions (Clive et al. 2005). As previous research has shown, undergraduate engineering students with little exposure to engineering design have had difficulties in understanding and conducting engineering design processes, leading to unsatisfactory academic performance and high dropout rate in engineering programs (Fantz et al. 2011). Therefore, engineering design should be introduced to students as early as elementary school levels rather than waiting until undergraduate stages. In the current study, we choose to focus on introducing engineering design to middle school students.

Previous research has identified that with increased exposure to engineering design activities, students' understanding of engineering design processes grows in various aspects to allow for more effective design practices. However, most of the existing studies have examined growth in undergraduate students' understanding of engineering design, such as comparing engineering students and experts' understanding of different aspects of the design process. For example, using verbal protocol analysis methods, Atman et al. (2007) examined the think-aloud of engineering experts and undergraduate engineering students while designing a playground. The analysis showed that, compared with undergraduate engineering students, the experts spent significantly more time on scoping design problems and collected information in more categories of design issues. These results indicate that gaining more experience in engineering design can help students focus on the fundamental aspects of the design process, such as clarifying the problems and goals. In addition to problem scoping, Atman et al. (2007) acknowledge that sketching, prototyping, and gesturing are important design processes, but those were not discussed in this research. Therefore, more research is needed to examine how students develop their understanding of sketching and prototyping, which are essential design processes in tasks that are suitable for younger students.

In the limited literature on younger students' understanding of engineering design processes, middle school students have been found to grow in design sophistication with increased exposure to design experiences. For example, English et al. (2012) examined seventh-grade students' design sketches for a bridge design task, first conducted as an in-class activity and later as a take-home assignment. Based on the content and structures of the drawings, English et al. identified six levels of design sophistication shown in the sketches. While sketches that show fixation on design materials are considered as showing low-level design sophistication, sketches that demonstrate explicit labeling and recognition of design structures (e.g., triangles, supporting bases) are considered as showing high-level design sophistication. Qualitative analysis of the students' sketches showed that more students created high-level sophistication sketches in the take-home assignment than in the in-class activity. However, English et al. compared students' level of design sophistication in sketching and across two time points—in-class and at home. It is necessary to investigate students' design sophistication and the understanding of design process in a wider range of design aspects and over a longer time span. Therefore, informed by previous research, we examined middle school students' understanding of engineering design processes, such as using sketching and prototyping to solve design problems during a 2-week toy design workshop.

Methods

Participants

Twenty-seven middle school students who attended a Toy Design Workshop at a Midwestern University in the USA participated in the study. The participants were between 13 and 14 years old (M = 13.21, SD = 0.83). Approximately 30% of the participants were girls. The Toy Design Workshop lasted for 2 weeks and was conducted twice consecutively in 1 month, with the same instructors and activities.

Fourteen students participated in the first 2-week workshop session, and another 13 students participated in the second 2-week workshop session. Three students were not able to finish all the surveys because they did not attend some of the sessions of the workshop due to issues beyond our control. The analysis of the self-efficacy survey and the engineering design processes survey focused on the 24 students who finished all the surveys.

Framework of the Workshop

The toy design workshop was structured to help middle school students learn about the iterative engineering design process through building relatable objects that they can play with. Throughout the various toy design activities, the students identified design goals, generated design ideas, built prototypes, as well as iteratively tested and modified the prototypes to build toys that can be played with and achieve real-world applications. The designing, making, and playing of toys not only added "play value" to the design process (Kudrowitz and Wallace 2009) but also provided a personally meaningful context for middle school students to learn about science concepts, such as gravity, forces, and pressure, and engineering concepts such as building solid structures, mechanisms, and electronics. Besides, as highlighted in the maker movement, students can reflect, refine, and represent their learning experiences through the making of physical objects (Kolodner et al. 2003; Peppler and Bender 2013). In this workshop, we integrated a total of five toy design activities—three of these focusing on designing toys with real-world applications and two activities focusing on specific design techniques, such as sketching to model design ideas. The setup and the sequencing of the activities were based on the progression of the underlying physics and design principles (see Table 1). For example, students began with the marshmallow activity, in which they learned about creating a solid-supporting structure. The marshmallow activity paved the foundation for building a solid-supporting base during the trebuchet and fan boat activities later in the workshop. At the end of each design activity, students were given time to play with their design products. Lastly, the class spent time reflecting on the design concepts in the design and making process. The reflection takes around 10–15 min in a 3-h session. Figure 1 shows illustrated examples of the major design activities in the workshop.

Marshmallow Challenge and Foil Boat

The marshmallow tower challenge and foil boat activities were conducted in the same 3-h session. The first part of the session was the marshmallow tower challenge, designed to help students identify basic engineering design principles for prototyping and building stable supporting structures (i.e., observe the influence of tension, compression, and bending on structure). Working in groups of 3–4, the students were given 20 spaghetti sticks, 1 yd of masking tape, and 1 yd of string to build a free-standing structure to support a marshmallow (Fig. 2a). The small group setting helped to foster collaborative experiences that are applicable to different types of projects in engineering. The goal of this activity was to create a tower with a marshmallow on top that was as tall as possible, using the provided materials. Following the introduction of the activity, students were given 20 min to work in small groups to design and construct the tower. At the end, the height of the tower was measured as the students placed the marshmallow on top of the tower. After the activity, the class debriefed on how to design and build a stable supporting structure and the importance of having a strong base in structures.

The foil boat activity was designed to help students realize the importance of iterative prototyping and identify factors that influence buoyancy, such as weight distribution, the surface area of the boat, and the volume of water displaced by the boat. Working individually, students were given 15 min to design a boat using a 6 × 6 in aluminum foil to hold as many nickels as possible in a tub of water (Fig. 2b). The students were encouraged to test their designs and modify the prototypes. At the end of the 15 min, the class discussed effective design strategies in making the foil boats. Then, the students were given 10 min to design a foil boat that held the highest number of nickels with the least amount of foil. The debriefing session following this activity helped students to identify design principles in buoyancy and weight distribution.

Nerf Blaster Dissection Activity

The Nerf blaster activity was structured as a product dissection activity to demonstrate the mechanics and structures involved in engineering design. Students worked in groups to dissect a blaster together while observing the mechanisms to launch the dart: electric pump, air bladder, piston and spring, and plunger and spring (Fig. 3a, b). Prior to dissecting the blaster, students were asked to predict how the blaster would work. Then, they opened the devices and compared what they saw with their predictions. The students were also tasked with creating a functional decomposition (Hirtz et al. 2002) chart that addressed the functionality of each of the components identified during the dissection activity. At the end of the activity, the class discussed the various design principles and system connections inside the blaster.

Sketching

This activity helped students to understand why sketching is important for engineering design. The structure of this activity was based on the prior work of (Hu et al. 2015) on the best sketching practices for designers. The first part of the activity

Table 1 Design concepts in the toy workshop activities

Activity	Learning/design goals	Design concepts/strategy	Potential sources for developing self-efficacy beliefs
Marshmallow tower	Design and build a marshmallow tower as tall as possible to hold a marshmallow.	Brainstorming design ideas in small group Structure Collaboration	Mastery experience • Generate and plan design ideas successfully to build the tower (design and sketching) • Build prototypes successfully for proof of design idea (prototyping) • Build the free-standing tower with the marshmallow on top with peers (collaboration) Vicarious experience • Observe how peers create prototypes of solid-supporting structure successfully (prototyping) • Observe how peers create sketches to plan for design of the tower (design and sketching)
Foil boat	Design and build a boat with foil to hold as many coins as possible without sinking in water.	Buoyancy in design Weight distribution	Mastery experience • Designed and modified prototypes of the foil boat to carry coins (design and prototyping) Vicarious experience • Observe how peers modify the prototypes of the foil boat to increase the capacity for carrying coins (design and prototyping)
Nerf blaster	Understand the inner working of the Nerf blaster and develop the functional decomposition of the Nerf blaster	Manufacturability Design for assembly Reverse engineering Kinematics	Mastery experience • Creating sketches of disassembled Nerf blaster (sketching) • Successfully identify the functions of the Nerf blaster parts after disassembly (design) Vicarious experience • Observe how peers create sketches of the disassembled Nerf blaster (sketching) • Observe how peers successfully explained the functions of the disassembled parts (Design)
Sketching	Develop communication skills using sketching	Fast idea visualization Communication	Mastery experience • Successfully create sketches of objects and design ideas (sketching) Vicarious experience • Observe how peers create sketches of objects and design ideas (sketching)
Trebuchet	Design and build a trebuchet with plastic pipes, connectors, and wood sticks to throw a tennis ball as far as possible.	Sketching Brainstorming design ideas in small group Structure Lever's principle Collaboration	Mastery experience • Successfully generate design ideas and sketch the design of the trebuchet (design and sketching) • Successfully create and modify the prototypes of the structure and the throwing mechanism (prototyping) • Work with the team to design and build a functional trebuchet (collaboration) Vicarious experience • Observe how peers design and sketch the trebuchet (design and sketching) • Observe how peers modify the prototypes of the trebuchet (prototyping)
Fan boat	Design and build a fan boat with foam board, fan, motor, and rudder, so that the boat would travel forward and turn directions.	Sketching Brainstorming design ideas in small group setting Structure Weight distribution Aerodynamics Collaboration	Mastery experience • Successfully generate and sketch design ideas of the fan boat (design and sketching) • Create and modify prototypes of a functional fan boat (prototyping) • Work with the team to design and build a functional fan boat (collaboration) Vicarious experience • Observe how peers generate and sketch design ideas for fan boat (design and sketching) • Observe how peers modify the prototypes to improve the controllability and speed of the fan boat (prototyping)

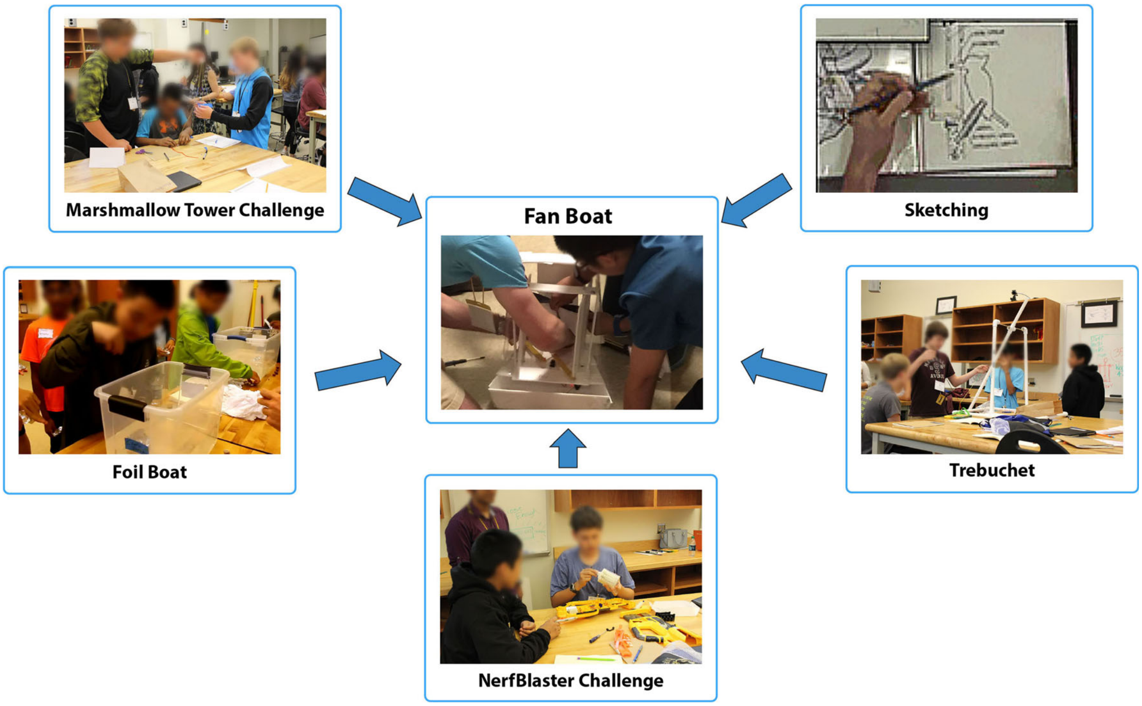

Fig. 1 Examples of workshop design activities. The final activity, fan boat, applied the design principles and processes introduced in earlier activities of the workshop

focused on the basic elements of sketching for engineering design and emphasized that the purpose of sketching is to visualize design ideas rather than create perfect-looking images. In this initial stage of sketching, we engaged students in warm-up sketching activities traditionally used in art design to prime the students for later tasks. The second part of the activity focused on sketching techniques such as using the straightness, thickness, and expressiveness of lines to visualize design ideas. The third part demonstrated how sketching is used in design to transition vague, tentative concepts to detailed, well-defined products. The final part of the sketching activity emphasized the importance of Boolean shape construction, showing context, motion or flows, and annotated sketches. Throughout this activity, we highlighted that the purpose of sketching is to create simple sketches to visualize, iterate, and communicate design ideas, rather than create perfect and detailed drawings.

Trebuchet

This activity was conducted in one 3-h session, with 1 h and 45 min of designing/building and 1 h of testing. During designing/building, students first observed real-life trebuchet examples, which helped to clarify students' confusion between trebuchet and catapult. Then, the students worked in groups of 3–4 to design and build a

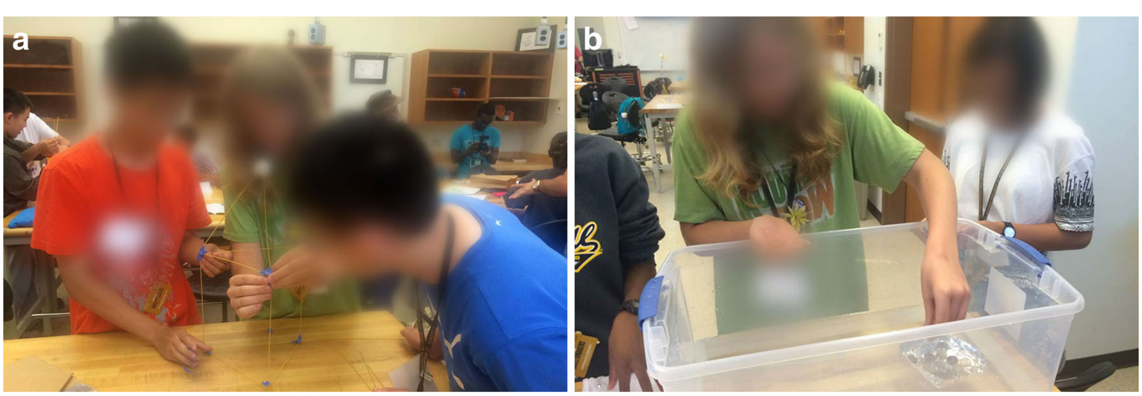

Fig. 2 **a** Constructing the tallest free-standing tower using spaghetti sticks to hold marshmallow at the top (*left*). **b** Designing and testing the foil boat that can hold the maximum number of coins with the least amount of foil (*right*)

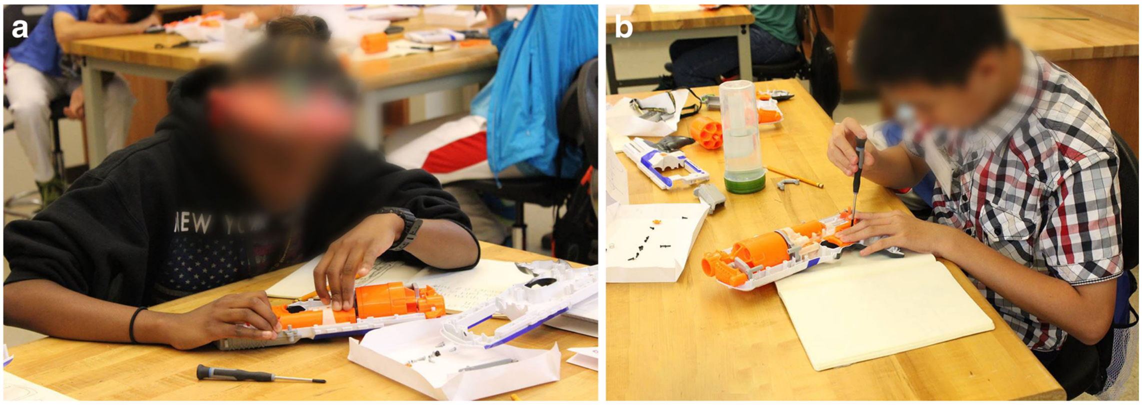

Fig. 3 Dissection of the Nerf blaster and classification of different components

trebuchet with given materials, including plastic pipes, wood sticks, small plastic bags, and connectors for connecting the pipes (Fig. 4a–c). Students were encouraged to apply lever principles and stable structures learned during the marshmallow challenge. At the end of the activity, students were taken to an open space to test their trebuchets and launched tennis balls as far as possible.

Fan Boat

This activity was designed to help students apply the concepts and design principles constructed in the previous activities, such as stable supporting structure, weight distribution, and lever principle, and also provide a platform to scaffold the design process understanding that they had gained in the first week of the workshop. This activity took three 3-h sessions, totaling approximately 9 h. Working in groups of 3–4, students designed and built a fan boat with foam board, the motor, fan, remote control-related components, various arts and crafts products (e.g., popsicle sticks, string, and hot glue), as well as acrylic control horns (i.e., a triangle-shaped device that connects the parts) (Fig. 5). While building, students were encouraged to apply the principles they learned of structures, weight distribution, energy transfer, and prototyping during their design and build processes. At the end of this activity, students tested their boats in a large open space location, where students used the remote control to maneuver the boat to cross a zig-zag-shaped obstacle course on a smooth linoleum surface. After testing the fan boat, the class discussed the design concepts used in the activity.

Measures

Engineering Design Self-Efficacy Survey

The Engineering Design Self-Efficacy Survey asked students how well they believed that they could perform in the engineering design processes. Survey items were developed based on an engineering design self-efficacy model and self-efficacy belief model proposed in previous studies (Carberry et al. 2010; Bandura 2006). The survey focused on four types of engineering design processes: sketching, prototyping, design iteration, and collaboration, which are often observed in middle school students' design activities. Students responded to the survey on a five-point Likert scale (1 = *strongly disagree*, 5 = *strongly agree*). The *sketching* subscale had four items; the prototyping subscale and collaboration subscale had seven items, and the *design iteration* subscale had eight items. To ensure the content validity of the items, we followed procedures recommended in Haynes et al. (1995). We first identified the definitions of the constructs by following previous

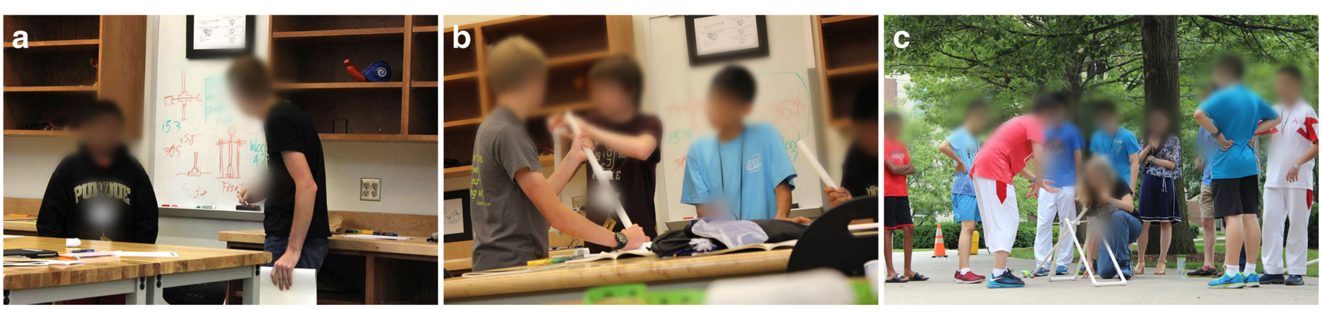

Fig. 4 Processes in designing and building the trebuchet. **a** Define design goals and create sketches on whiteboard (*left*). **b** Prototyping with materials (*middle*). **c** Testing trebuchet (*right*)

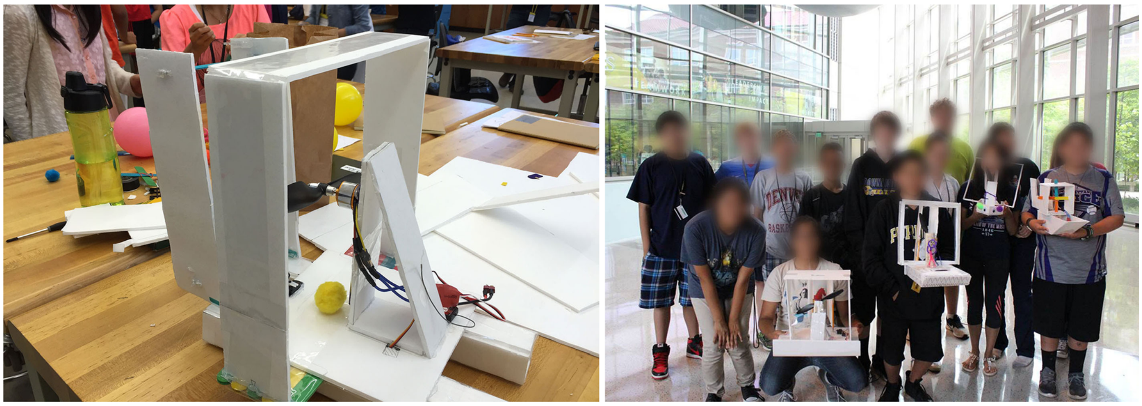

Fig. 5 Final prototypes of the fan boat

models on engineering design self-efficacy (Carberry et al. 2010). Then, we consulted engineering design domain experts regarding the content validity of the items. The survey had a total of 26 items and showed reliability Cronbach's $\alpha = 0.86$, which is sufficient for this type of survey (Mccoach et al. 2013). Sample survey items are listed in Table 2.

Engineering Design Process Surveys

Open-ended surveys were designed to assess students' understanding of the engineering design process. The surveys were designed specifically for each of the major design activities—marshmallow tower, trebuchet, and fan boat, covering topics on planning, prototyping, and testing in the engineering design process. Sample questions in the survey include the following: "While making the things you designed, have you had to restart? What were the things you need to change or remake?"; "Given more time, what would you do to improve your designing/making to achieve your design goals?"; and "If you are going to teach your friends at school about designing a marshmallow tower, what would you tell them?".

Procedures

Participants received self-efficacy surveys at the beginning and the end of the 2-week workshop. Participants also completed the engineering design process surveys for the three major design activities—marshmallow tower, trebuchet, and fan boat, which were introduced, respectively, at the first day, the fourth day, and the eighth day of the workshop. During the workshop, the students worked in groups of 3–4 students for 3 h daily. One instructor and several assistants, including undergraduate and graduate students in mechanical engineering, provided assistance when the participants requested for help with cutting materials or assembling the structures.

Table 2 Engineering design self-efficacy survey sample items

Subscale	Sample items
Sketching	I feel very comfortable with sketching
Prototyping	I feel confident that I can create a working model of my idea
Design Iteration	I feel confident that I can figure out what needs to be improved when I design something
Collaboration	I feel that I can trust my teammates

Full survey is available upon request from the corresponding author

Findings

Self-Efficacy Beliefs in Engineering Design

To answer the first research question (*What is the influence of the toy design workshop on students' self-efficacy in engineering design?*), we compared students' self-efficacy before and after attending the workshop. Three of the 27 participants did not finish both the pre and post surveys. We analyzed the remaining 24 students' responses to the pre and post survey using paired sample t test. Results showed significant increases in students' self-efficacy in engineering sketching ($t(23) = -3.97$, $p = 0.001$, $d = 0.64$), design iteration ($t(23) = -5.38$, $p < 0.001$, $d = 0.97$), and prototyping ($t(23) = -4.69$, $p < 0.001$, $d = 0.97$), from before to after attending the workshop, but students' self-efficacy in collaboration during design did not change significantly ($t(23) = -1.63$, $p = 0.116$, $d = 0.34$). See Table 3 for means and standard deviations for the four types of processes included in the self-efficacy survey.

Students' Understanding of the Engineering Design Processes

To answer the second research question (*What is students' understanding of the engineering design process during the toy design workshop?*), we analyzed each participant's responses to the three sets of engineering design processes

Table 3 Descriptive statistics for self-efficacy survey responses

	Pre-survey			Post-survey		
	n	Mean	SD	*n*	Mean	SD
Sketching	24	14.38	2.57	24	15.96	2.40
Prototyping	24	24.88	3.99	24	28.54	3.58
Design iteration	24	29.63	4.28	24	33.58	3.82
Collaboration	24	28.08	4.20	24	29.54	4.32

surveys for the three major design activities— building a marshmallow tower, a trebuchet, and a fan boat. The coding of survey responses focused on identifying design processes that were highlighted by students as essential to their design activity. Two coders coded the responses independently, based on conceptual frameworks in design thinking and design processes (Booth et al. 2016; Carberry et al. 2010; Clive et al. 2005; English et al. 2012; Kolodner et al. 2003; Peppler and Bender 2013). Then, the two coders discussed the codes and reached agreement on assigning all the survey responses to nine coding categories: *sketching*, *prototyping*, *design goals*, *inference/predictions about design*, *generate design ideas*, *design of structure*, *design of system/process*, *materials*, and *collaboration*. A third coder was used to check the reliability of the coding process by coding one third of the responses and reached agreement Cohen's kappa = 0.87, $p < 0.001$. Table 4 shows the definitions of the coding categories and examples of student answers for each category.

Examples of sketching include students describing sketching as an important step in the design process. For example, in response to the question on what the students would share with friends about what they had learned during the Trebuchet activity, one student responded "You must sketch first, think carefully, and start making." which indicated that the student understood the importance of creating a sketch before building. Prototyping was used when students described the role prototyping as well as making changes to prototypes play in the design process, which reflects the iterative nature of the design process. For example, one student wrote "I want to be able to design elaborate prototypes of models," and another student wrote "I had to change to make an improved prototype and did." In both of these answers, students mentioned prototyping as an important part of the engineering design process or as a goal, even though the questions did not focus on prototyping. The next category, design goals, included any responses in which students reflected on the goals for the task to be completed. For example, when asked about what they need to keep in mind when building the tower, one student wrote "It needs to be balanced, and it must stand up by itself." The make inferences/predictions about design code was used when students used prior knowledge (e.g., knowledge of physics) to predict what was going to happen during the design process. One student wrote "The

Table 4 Coding category and example coded responses

Coding category	Definition	Coded examples
Sketching	Students describe sketching as a necessary step in design	"You must sketch first, think carefully, and start making."
Prototyping	Students describe making prototypes of ideas and making changes to prototypes as part of the design process	"We had to restart and redo the base" "To make it stand straight we added a bottom to it and it almost worked"
Design goals	Students describe indicators reflecting the design goals of a given task	"It (the marshmallow tower) has to stand perfect and be the tallest" "to make the trebuchet to throw the tennis ball a far distance"
Make inferences/predictions about design	Students make inferences and predictions about design based on their prior knowledge	"The supporting structure should be able to distribute the force, or it will break."
Generate design ideas	Students describe mentally thinking about design ideas as a component of the design process	"When we design something, we need to consider more factors."
Design of structure	Students describe the structural aspect of the design	"Have a stable fulcrum, [and] appropriate ratio between the beams on both sides" "Triangles are good shapes that can let the tower stand, then we can build it higher."
Design of system/processes	Students describe the design as a system and talk about how it interacts with the people and environment surrounding the design	"Also I would tell them to have a good cage around the fan so it is safe."
Materials	Students describe the details of the materials given for the design tasks	"The tape is cheap, so use it as much as needed." "The tape is not sticky."
Collaboration	Students describe working with others and working in teams as a component in design	"discussing with teammates" (in describing how they overcome challenges in design and making)

force beam should be short; the object beam should be long." when asked what he/she would share with friends about the Trebuchet activity. Generate design ideas involved students describing the process of generating ideas as part of the design process, and examples of student responses include "I just brainstormed ideas" and "we got an idea from the video." Both of these answers were given when students were asked about what they did when they felt stuck during the design/making process. These are examples of how students in this workshop understood that there are multiple solutions to the problems they were presented with and that generating new ideas can help. Design of structure was used when students' survey responses focused on the importance of structures for completing the tasks. For example, when asked about ways to improve their designs, one student wrote "add more supports and reposition parts of the tower" and another one wrote "balance the weight out more and try to use the bigger fan blade." The design of system/processes category was used when students described design as a process that includes the people and environment surrounding the design. For example, one student stated he would tell friends to make the fan boat "lighter, make a connect to the boat, [and] the propeller has a protection," and another one wrote "do your best and make it not to hurt anyone." Both of these answers indicate that students were aware that their designs interact with the environment. Materials reflected an emphasis on materials students received to complete the design tasks. Examples of student answers include "Trebuchets can only be built with a lot of PVC pipes and a reference model and picture or else it'll be impossible" and "How fragile the sticks are, and how limited the supplies are," which were provided in response to questions about what they would share with friends about the trebuchet activity and what they had to keep in mind to meet the design goals for the marshmallow challenge. Students were not asked specifically about materials, but their answers focused on the role the materials available and the amount of materials they used played in completing the tasks. Finally, collaboration involved the collaborative nature of the design process, especially in situations when students work in teams to complete a design task and recognize the importance of being able to work with others. In response to the question about what they did when they felt stuck during the design process, one student responded "we thoroughly explained each of our designs and chose what we thought was the best one," which indicates that there was true collaboration taking place in that team, so much that they were able to compromise and chose the best solution to the problem at hand when necessary. Another student stated "I talked to the group and shared ideas," again in response to the question about what his/her team did when they felt stuck.

After assigning codes, we summarized the raw coding frequency by activity. We also weighted the raw coding frequency based on the total number of student responses that were coded for an activity to account for student absence or no response. Table 5 presents each activity's raw and weighted percentage coding frequency. Because the three design activities were introduced at different time points (i.e., the first, fourth, and eighth day of the 2-week workshop, respectively), we compared the coded responses across the nine coding categories and also across the three time points. Among the nine categories, students made the most references to design of the structure throughout the three activities in the workshop. In addition, although some categories (e.g., sketching, inferences/prediction about design, generate design ideas, design of the structure, and design of the system/processes) show an increasing trend from the first to the last activity, other categories such as design goals and materials show a decreasing trend from the first to the last activity. Besides, students described prototyping and collaboration with similar frequency from the first to the last activity. However, although the frequency of collaboration remained somewhat stable throughout the three activities, there were instances when students made negative references to collaboration in the survey responses after the last two activities (e.g., "I want to tell others to not shout at your teammates during discussion"). Negative references were not coded as collaboration because the negative references do not reflect the students' understanding of the design process, which is the goal of the coding analysis.

Discussion

This study contributes to the literature on engineering design learning by showing that engaging middle school students in hands-on toy design activities facilitate their understanding of the engineering design processes and self-efficacy beliefs in engineering design. This study also demonstrates toy design modules that can be adopted to foster students' self-efficacy beliefs and understanding of engineering design processes.

The Influence of Toy Design Workshop on Self-Efficacy

Our findings suggest that participants' self-efficacy in sketching, prototyping, and design iteration increased significantly after attending the toy design workshop. Although previous research has suggested that involving students in engineering-related activities promotes self-efficacy in engineering in general (Fantz et al. 2011), this study demonstrates that hands-on engineering design activities can increase middle school students' self-efficacy in engineering sketching, prototyping, and design iteration.

Drawing from empirical evidence on the sources of self-efficacy in engineering (Hutchison et al. 2006), participants in the current study may have developed self-efficacy beliefs through mastery and vicarious experiences. Consistent with

Table 5 Coding frequency and percentage weighted by the number of total coded statements for each activity

Activity	Sketching	Prototyping	Design goals	Make inferences/ predictions about design	Generate design ideas	Design of the structure	Design of system/ processes	Materials	Collaboration
1	0 (0%)	11 (35.52%)	18 (68.65%)	4 (11.32%)	5 (29.85%)	34 (24.20%)	0 (0%)	16 (90.58%)	6 (32.56%)
2	2 (36.10%)	12 (34.21%)	4 (13.47%)	24 (59.95%)	8 (42.16%)	64 (40.21%)	1 (2.96%)	1 (5.00%)	7 (33.53%)
3	4 (63.9%)	12 (30.27%)	6 (17.88%)	13 (28.74%)	6 (27.99%)	64 (35.59%)	37 (97.04%)	1 (4.42%)	8 (33.91%)

Activity 1 is marshmallow tower challenge; activity 2 is designing a trebuchet; activity 3 is designing a fan boat

the benefits of mastery experiences shown in previous research, students' successful experiences of conducting design activities in the current study may have promoted their self-efficacy (Hutchison et al. 2006). For instance, we structured the toy design workshop as a material-rich environment, where students gained successful sketching, prototyping, and design iteration experiences as they engaged in hands-on activities and went through the engineering design cycles. In contrast with more advanced engineering design activities, such toy design activities can be especially beneficial for middle school students: toy design is inherently interesting and allows students with varying degree of prior knowledge and skills to participate in the design process.

According to previous research (Plant et al. 2009; Hutchison et al. 2006), the current study may also have promoted students' self-efficacy in engineering design through vicarious experiences. For example, students worked on the design tasks in small design teams and observed peers during the design process. There were also advanced undergraduate and graduate mechanical engineering students serving as coaches for the students during the workshop. Observing coaches' and peers' design behaviors provided students with vicarious experiences and may have facilitated students' self-efficacy in accomplishing similar design tasks (Hutchison et al. 2006).

However, students' self-efficacy with regard to collaboration during design did not change significantly after participating in the workshop. A potential explanation for this finding can be drawn from students' responses to the engineering design process survey. Although the survey responses showed that students gradually acknowledged the advantages of collaboration during design, students also described the negative experiences they had in collaboration, such as concerns of teammates' approach to communication (e.g., shouting) during group discussions. Similar negative experiences may have prevented students from obtaining mastery experiences that support the development of self-efficacy beliefs in collaboration in engineering design. Considering the prevalence and challenging nature of collaborative engineering design tasks (Dong et al. 2004; Reid and Reed 2005), results from this study corroborate the necessity to provide additional support, such as training in collaboration techniques, to promote students' self-efficacy beliefs in collaborative engineering design activities.

Understanding Engineering Design Processes

Students' responses to the open-ended surveys demonstrate that they were able to highlight important aspects of the design process, such as prototyping, design of the structures, and collaboration as they engage in engineering design activities. In addition, students may have recognized the role of the different aspects of the design process as their exposure to design activities increased over time during the workshop. Specifically, compared with the beginning activity of the workshop, in later design activities, the students increasingly described sketching, inferences/prediction about design, generate design ideas, design of the structure, and design of the systems/processes as important components of the design process. This finding is consistent with results from previous research on design thinking, which indicate that, as students gain experiences with design, they shift their focus from the peripheral (e.g., focused on minute details, such as the characteristics of the materials: "The tape is not sticky") to the substantial aspects of the design process (e.g., focused on the fundamental elements in design, such as design of the structures: "Have a stable fulcrum, [and] appropriate ratio between the beams on both sides") (Atman et al. 2007; English et al. 2012; Mentzer et al. 2015). Additionally, considering that prototyping design ideas plays an important role in the design process (Atman et al. 2007), realizing the necessity of sketching and prototyping can benefit students' later engineering design practices (Faas et al. 2014).

Consistent with previous results where increased experiences in design lowered students' fixation on minute details and single solutions (Mentzer et al. 2015), we identified that students showed decreasing frequency in talking about the details of design *materials*, such as the stickiness of the tapes. Such change can be attributed to students' gaining insights into the underlying design processes, leading to decreased emphasis on non-essential and minute design details.

It is also important to note that students' references of design goals became less frequent as they moved towards later activities. This is a surprising finding given that students' references to other fundamental aspects of the design process, such as design of the structure, increased as they progressed through the toy design workshop activities. A potential explanation for this finding is that activities that involve multiple steps and the coordination of various parts may obscure the design goals. Students' difficulties in identifying clear design goals in more open-ended and complicated tasks have also been documented in other studies involving design thinking and problem-solving processes (Hirtz et al. 2002; Kolodner et al. 2003). Such results suggest the necessity to help students clarify and refocus on design goals throughout complicated design tasks.

Implications

In summary, findings from this study suggest that engaging middle school students in engineering design tasks through a toy design workshop can enhance their self-efficacy and understanding of engineering design processes. By providing experiences that contribute to the development of self-efficacy, such as mastery experiences and vicarious experiences, the toy design workshop can promote middle school students' self-efficacy in engineering design. Through participating in the iterative processes of engineering design, middle school students can understand and identify the essential aspects of the design process. Such results suggest the necessity to engage middle school students in engineering design activities to facilitate their self-efficacy and understanding of design processes.

This study also implies that the current toy design workshop framework, which scaffolds students' understanding of design processes, has advantages for young students. Rather than randomly introducing complicated and irrelevant design activities, we selected activities with interconnected design principles that complement one another. We also arranged the activities in a sequence that begin with introducing basic design principles and culminate in a final project that connects the design principles and processes. Furthermore, in between the design activities, there were sessions devoted to emphasizing essential design processes, such as sketching and dissecting toys that are the results of engineering design. Based on our current study, we recommend that educators consider applying such framework when structuring design workshops for young students.

Limitations

This study had limitations in sampling and the duration of the workshop. Because the participants self-selected to attend the toy design workshop, they may have had strong initial interests in design and making. Thus, results may not be applicable to populations with few initial interests in design. Another limitation of this study is the short duration (i.e., 2 weeks) of the workshop. Given more time, students may have demonstrated more prominent changes in attitudes and the understanding of design processes. Future studies should engage students in design activities that span over longer durations.

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