

Developing Middle School Students' Engineering Design Concepts through Toy Design Workshop (Fundamental)

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Introduction

Middle school students are at a critical developmental stage for understanding and applying engineering design concepts, which are the foundation for solving engineering design problems. Real-world engineering design problems, widely known as ill-defined, rely heavily on embodied interaction and prototyping techniques¹. However, traditional classroom activities emphasize well-defined problems and encourage students to manipulate abstract symbols such as physics or mathematical formulas to identify solutions. Such reliance on abstract operation, along with having little experience of concrete modeling through embodied and prototyping techniques, has led students to face great challenges when entering engineering programs². Therefore, middle school students need increased exposure to engineering design experiences that transform their “habit of the mind”—from fixating on thinking-before-prototyping towards prototyping-to-think.

In this study, we structured a toy design workshop to provide hands on and engaging design activities for middle school students, to help them develop self-efficacy beliefs in design, model and scaffold engineering design mindsets, and apply design concepts in engineering design. The research questions we intend to address include:

1. What is the influence of the toy design workshop on students' self-efficacy?
2. What is the influence of the toy design workshop on students' application of engineering design concepts during design?

Theoretical framework

Self-efficacy in Engineering Design

Engineering design self-efficacy is the degree to which students believe they can excel at tasks related to design and making³. Social cognitive theory and previous research has suggested that students' self-efficacy beliefs are under the influence of mastery experiences, vicarious experiences, physiological states, and persuasion⁴; and such beliefs play an even more dominant role than actual academic achievements in career choices and the willingness to persist through challenges⁵; Thus, students who have little mastery or vicarious experience in design and making may develop relatively low level of self-efficacy beliefs in engineering design, which if persisted, can prevent students from enrolling in engineering programs or pursuing engineering as a career⁵; and for students who are enrolled in engineering programs, such low self-efficacy beliefs in design and making would have adverse influence on their motivation and performance⁶. Therefore, the goal of the current study is to provide learning environments that foster positive self-efficacy beliefs in design, prototyping, making, and collaboration for middle school students, so that students can develop positive attitudes towards processes that are integral to engineering.

As identified in earlier work, students' pre-collegiate experiences with engineering have significant impact on self-efficacy beliefs⁷. Fantz et al.⁷ conducted a quasi-experimental study where they surveyed engineering students' 53 type of pre-collegiate experience with engineering,

such as having robotics as a hobby, having formal engineering classes, or attending single/multi-day workshops; the researchers also used questionnaires to assess engineering students' self-efficacy. For each of the 53 types of experiences, the researchers compared students' engineering self-efficacy between those who had a specific type of experience with those who did not have the same experience. Results showed that overall, engineering students' experiences with engineering before attending college is positively associated with self-efficacy beliefs. The finding also indicated that students who had engineering-related hobbies and attended formal engineering curriculum in secondary schools reported significantly higher levels of self-efficacy than those who did not have such experiences. However, this study examined self-efficacy by asking students to recall prior life experiences. It is necessary to also examine students' in-situ development in self-efficacy from participating in pre-collegiate engineering activities.

Previous research has also examined influential factors for engineering students' self-efficacy in college level engineering courses. In a study by Hutchison et al.⁸, first year engineering students attributed being able to do well in an engineering course to a variety of reasons, ranging from exam/homework grades to enjoyment, and motivation for doing well in the class. The attributions are coded and categorized into 9 major factors, and were associated with the four major sources of self-efficacy beliefs identified by Bandura et al.⁵, including mastery experiences, vicarious experiences, physiological states, and social persuasion. For instance, the factor "understanding or learning of the material" is identified by Hutchison et al.⁸ as exemplary of mastery experience—one of the most prominent sources of STEM self-efficacy beliefs⁹. This research provides concrete examples of what factors first year engineering students attributed to for their self-efficacy beliefs in an introductory engineering course. The factors cited by the students exemplify the classical framework of the four major sources of self-efficacy beliefs in the context of engineering learning. However, this study asked students to list and rank the influential factors at the beginning of the course, and did not show whether students improved in their self-efficacy beliefs through experiences related to these influential factors.

Previous research that examined the change in middle school students' self-efficacy has utilized a variety of intervention approaches, including having students interact with computer-based agent. In a study by Plant et al.¹⁰, middle school students were randomly assigned to interact with either a male or female computer agent, or no computer interaction during a class session. The results showed that students increased in their self-efficacy in engineering from interacting with the computer-based agent. However, this study implemented the virtual agents to provide narrative accounts of engineering as a profession, where students merely watched the computer agents, rather than engaged in hands-on activities related to engineering design.

In summary, previous research has mainly focused on associating early life experiences with students' self-efficacy. Limited research has been done on enhancing self-efficacy through engaging students in learning environments that encourage hands-on activities. Therefore, in this study we intend to address this gap in literature by demonstrating an engineering design workshop that engage students in hands-on activities and investigate if such experiences would increase students' self-efficacy. In alignment with social cognitive theory and its implications on the sources of self-efficacy, we intend to provide the types of experiences highlighted as crucial to the development of self-efficacy, such as mastery experience, through students' participation in design and making; vicarious experience, through students' engagement in group hands-on activities; physiological state, through having students work on tasks that are enjoyable, and

social persuasion, through instructors' constant verbal comments that acknowledge students' progress and improvement.

The Development of Design Concepts

In alignment with the societal emphasis on nurturing next generation makers and tinkerers, it is imperative to teach students design concepts from an early age. One of the major design concept components is design thinking, which is the thinking process generally adopted by engineering designers in approaching design problems¹¹. Effective design thinking has been commonly qualified as going through the process of planning, building, and testing, or in more details, going through the cycle of identifying problems, building prototypes, iteratively modifying prototypes, and communicating design solutions¹². Although skillful application of such mindset often determines the efficiency of an engineering designer, the adoption of such thinking strategy is not intuitive and requires training. More importantly, it has been observed that in undergraduate level, difficulties in applying such mindset has challenged engineering students, leading to unsatisfactory academic performance and high dropout rate. Therefore, researchers have advocated that the design thinking mindset should be introduced to students early in life rather than waiting until undergraduate levels.

Existing research on design thinking has mainly examined this concept at the undergraduate and above levels. In an exploration of professional engineering designers' perception of design, Daly¹³ identified that design thinking is non-linear, and iterative. Using a phenomenology qualitative method, Daly also identified that professional engineers across several engineering disciplines considered design as evidence-based decision-making, organized translation, personal synthesis, intentional progression, directed creative exploration, and freedom. The researchers highlighted that the types of engineering design experiences influence the design lens adopted by designers, which would then influence how designers approach design problems. Such findings suggest that there are commonalities in what constitutes effective design thinking strategies.

What are the commonalities in effective design thinking strategies? And how have researchers examined design thinking? Atman et al.¹⁴ examined the design thinking process among engineering experts and engineering students. Using verbal protocol analysis methods, Atman asked expert engineers to design a playground in lab settings, and think-aloud the design process. Compared with undergraduate engineering students, the experts spent significantly greater amount of time on scoping design problems, and collected significantly more information belonging to a greater variety of categories. Atman pointed out that they chose to focus on five themes in the engineering design process, including problem scoping, project realization, alternative solutions generation, distribution of activity over time, and solution quality, while acknowledging that other elements such as sketching, prototyping, and gesturing carry equal weight, but is not discussed in this research. Atman also indicated that four of the five themes are quantifiable through a count of time spent on task, such as the amount of time gathering information and the number of times requesting information. The finding showed that expert engineers spent higher amount of time gathering information and request information more frequently, which indicate that as students progress through their design experiences and trainings, they may allocate time differently in the design process. Therefore, in our current research, we hypothesize that middle school students would gradually allocate time differently throughout the two-week workshop. However, because Atman et al. did not examine sketching

and prototyping in their study, there is a lack of previous research on how students who are novice to engineering allocate time as they gain in experience with engineering.

Design Learning through Situated and Embodied Processes

Engineering design is often embodied in concrete objects and tangible materials. As such, embodied cognition, the concept that cognitive processes are not just carried out in our head, but are also embodied in concrete objects and things, has important role in engineering design. One of our goals in this study is to investigate if engaging students in material-rich and hands-on engineering design workshops can enhance students' awareness and the adoption of building prototypes to think and develop design ideas.

Although there has been limited research on embodied cognition in engineering learning, the existing research has suggested that constructing learning environments with tools and objects provides benefits for engineering design learning. In a study by Roth¹⁵, fourth and fifth graders engaged in an engineering design curriculum, which included design activities such as building structures of bridges and towers with given materials. It was found that the students' engineering design learning increased in several aspects through students' interaction with tools, materials and artifacts in the environment. For instance, Roth observed that when two students worked together to construct a bridge, their initial planning mainly involved more abstract operations such as calculating parameters with formula. However, as the students started interacting with physical objects and went through repeated cycles of testing and modifications, the students diverted from the predefined plans consisting of sketches and formulas, and spontaneously invented ways such as layering materials to increase the strengths of the bridge. Such result emphasizes the importance of encouraging students to engage in embodied cognition and manipulate concrete objects or artifacts to integrate "thinking and acting"¹⁵ in the design process. However, this study mainly described a time slice in the design process and did not provide a continuous account of how students developed in design knowledge and the application of embodied cognition over the course of the engineering curriculum. In this current study, we intend to demonstrate how students progressed in design mindsets as related to embodied cognition over time.

Currently, research on embodied cognition and its influence in engineering design learning settings have been limited. There is a dearth of research in this area on assessing design learning in terms of using artifacts and prototyping to guide thinking. In this study, we incorporate research on design thinking and embodied cognition to propose a coding scheme that enables the examination of younger learners such as middle school students' development of design thinking using the perspective of embodied cognition. Besides, students would miss the opportunity to identify promising solutions if they have not played with the objects and prototype possible solutions embodied in objects. In previous research, students have been found to fail to prototype with objects early on in design stage for a variety of reasons, including lack of self-efficacy in design and making, or have not developed the prototyping mindset, which is essential to the design thinking process⁸. In this study, we intend to provide a material rich engineering learning environment and encourage middle school students to actively use embodied cognition approaches and identify solutions through prototyping and making.

Methods

Participants

Students were enrolled from a Toy Design Workshop conducted at a Midwestern University. All the participants in the workshop agreed to participate in the study. The participants are middle school students from the United States, China, South Korea and Columbia, who signed up for a summer camp that offers different types of classes at the University. Students who attended the Toy Design Workshop selected the workshop voluntarily when they signed up for the summer camp. Although some of the participants are English Language Learners, the participants' language proficiency was pre-examined by the summer camp organizers to ensure that the participants have satisfactory language skills to attend classes with English as the major instruction language. Fourteen students participated in the first two-week workshop session (Workshop1) and another thirteen students participated in the second two-week workshop session (Workshop2). The participants are between 13 to 14 years old. The two sessions were held consecutively in one month and provided the same instructors and activities. See table 1 for demographic information of the participants.

Table 1

Demographic information of participants

	Gender		Native Language			
	Male	Female	English	Spanish	Chinese	Korean
Workshop1	8	5	10	2	0	1
Workshop2	10	3	3	0	10	0

Framework for the Workshop

The workshop is set up in a way to immerse middle school students in material rich environment and learn about engineering design through hands-on engineering design and making activities. The activities are focused on designing and making toys that have real-world applications and can function through the mechanics to achieve certain design goals. The elements of toy building, functional for real-world applications are especially important, as toys provide a common ground to connect engineering with students' prior knowledge in life and school, thus promoting meaningful learning; and helps students to see the application of design concepts in authentic settings, thus allowing students to have real-life mastery experiences and adopting designer-like mindsets to solve authentic problems.

Measures

Self-efficacy survey. The self-efficacy survey was designed following the model in Carberry, Lee and Ohland³. The survey contained 26 items that ask about students' belief in doing well on specific tasks related to sketching, prototyping, design and collaboration. The pre and post self-efficacy surveys have identical items and are conducted before the first workshop session and after the last session.

Video analysis protocol. A video protocol was developed to assess students’ design processes. Previous research has identified that as students’ experience with engineering design develop, they tend to go through increasing iterations of design cycles—problem scoping, developing alternative solutions, and project realization¹⁴. While previous research focused on experienced designers at the undergraduate or above levels, this study investigates middle school students’ design processes and demand new coding categories appropriate for this group. Therefore, we conducted trial coding sessions to determine the major coding categories. In trial coding, 4 graduate students in mechanical engineering and one researcher in education coded the same randomly selected design session independently: they paused at 30 seconds intervals and generated descriptive codes for the design process based on previous literature. Following the trial coding, the coders discussed the observations and codes as a group and consolidated their coding into major categories: the students went through the design cycles of *planning*, *building* and *testing*, by either *verbally* talking to others in the team, *visually* checking the designs, or *physically* gesturing the design ideas and *tangibly* manipulating the design objects. Therefore, we generated three major coding categories based on the type of activities in the design process: *planning*, *building* and *testing*, and divided them into three sub categories based on the modality of the activities: verbal/abstract, visual/virtual, and physical/tangible. The coding protocol is presented in table 2.

Table 2

Video Analysis Protocol of Design Processes

			Activity in the Design Process		
			<i>Plan</i>	<i>Build</i>	<i>Test</i>
Modality	<i>Verbal/abstract</i>	Design Activity	Write/talk about design ideas	Suggest ways of combining materials in building	Discuss evaluations
		Example	Student(s) talk to groupmates about potential design ideas or write down the design ideas	Student(s) make suggestions about procedures/actions involved in building	Student(s) discuss the performance of the prototypes or design outcomes
		Coded example	“We should have a strong base, and stick the sticks together”	“where is the tape?, tie the tape here”	“It is not sticking with each other”
	<i>Visual/Virtual</i>	Design Activity	Sketch	CAD	Visual inspection of a built part
		Example	Student(s) sketch their ideas	Student(s) model their ideas in a CAD software	Student(s) observe the performance of the prototypes or design outcomes
		Coded example	Sketch the front view of a tower on a notebook before building	N/A	Watch the changes in the tower as a marshmallow is placed on top

	<i>Tangible /Physical</i>	Design Activity	Place objects together	Prototyping or building w/ physical materials	Apply force/weight (implicit/explicit)
		Example	Student(s) try fitting the materials together without fixating/attaching materials	Student(s) combine the materials in a certain position, or orientation	Student(s) lay force/weight on the designs or let the designs stand free (implicit loads being the weight of the structures themselves)
		Coded example	Students try putting several sticks together (without taping or fixating) to form a “A” shape to see if it looks stable	Students tape the sticks together to form a base of the tower	Place the marshmallow on top of the tower and see if the structure would stand or fall.

The students worked in small groups of three to four during the design sessions. Using the coding protocol, students’ collaborative design behaviors are coded as one of the following categories.

Verbal/abstract planning. This category describes the verbal or written communication the students make during their design process such as problem definition, potential solutions, and next steps. This type of planning relies more on abstract verbal communication in spoken and written forms.

Visual planning. Students sketch their ideas on the whiteboard or design notebooks. They create visual prototypes to plan the design ideas.

Physical planning. Without fixating the materials, students manipulate the materials to find out its properties and try out different possibilities.

Verbal building. Students give verbal instructions to team members on how to combine the materials during the building process. This category is different from the verbal planning in that the students are in the building stage of the design process, where parts of the design ideas have been built.

Visual/virtual building. In certain activities, students can build models on computers in a virtual environment, such as in CAD software. However, for the design activities in this paper, although we showed students how to use CAD software, and allowed them to choose to build models using CAD, none of the teams chose to work on the computers to build their designs. Therefore, we included the visual/virtual building category in the protocol, but did not use this code in the actual coding of the design sessions.

Physical building. Students built the design products by physically manipulating the objects and materials.

Verbal testing. Students talk about the performance of the design products, and making inferences about what can be done to improve on the results.

Visual testing. Students visually examine the quality, such as stability and efficiency of the products.

Physical testing. Students put on external forces to check the stability and efficiency of the prototype or design products.

Design quality rating scales. We developed design quality scales to assess students' design products in terms of the quality of the design. There exist a number of metrics that evaluate concepts and ideas: Kudrowitz and Wallace¹⁶ provide an excellent compendium of these metrics, observing that the most prevalent dimensions used in such evaluations are novelty and quality/relevance. For the purpose of our study, we chose to evaluate the concepts on the dimensions of design quality, using a five-point scale for each dimension. In order to aid the judge in rating each design on this scale, we provided them with decision trees. Using a decision tree rather than a standard Likert scale provided a more specific way to evaluate the designs, and in the case of disagreement among the judges, an effective way of identifying the reason for disagreement. See figure 1 for an illustration of the decision tree.

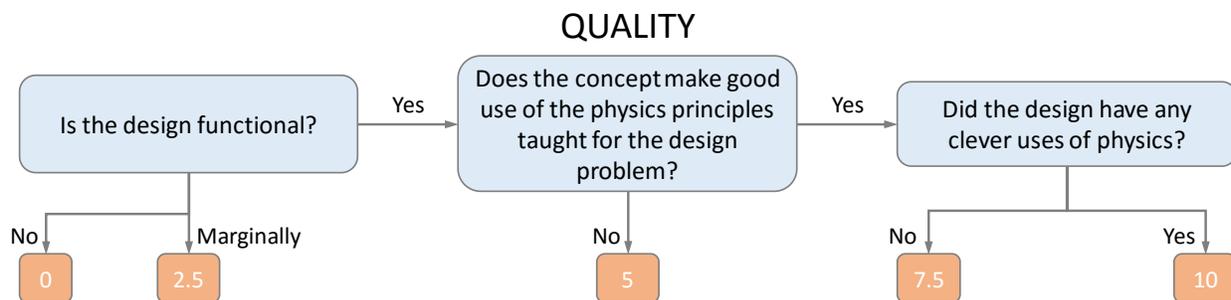


Figure 1. Design quality rating scale using decision tree format

Procedures

At the beginning of the two-week workshop, students filled out a self-efficacy questionnaire that asked about their level of self-efficacy beliefs in engineering sketching, designing, prototyping, and collaboration. There are six major activities for the workshop, including the Marshmallow challenge and foil boat activity, NERF Blaster Dissection, the Trebuchet activity, and the fan boat activity. On each day of the workshop, the students come to the design lab and work on an activity in small groups (3-4 students) for three hours, except when they take short 10 minutes breaks during the session. The design lab is set up in a way to assemble design workshops or studios in engineering settings. Four large work benches are set up in the middle of the room, with cabinets and whiteboards on both sides of the room to serve as additional work stations. The design sessions are video recorded to facilitate analysis of the design activities. One instructor and four to five assistants, from undergraduate and graduate levels in mechanical engineering, are available to interact with the students on each day of the workshop. The instruction is revolved around teaching students about design concepts through hands-on toy design activities. Table 3 presents the design concepts in the six activities.

Table 3

Design Concepts in the Toy Workshop Activities

	Design Goals	Design concepts
Marshmallow	Design and build a marshmallow tower as tall as possible to hold a marshmallow.	Brainstorming time management safety strength of materials Team work
Foil boat	Design and build a boat with foil to hold as many coins as possible without sinking in water.	Boat design
Nerf Blaster	N/A	How to manufacture parts, how systems work, using existing devices to borrow ideas
Sketching	N/A	How to rapidly visualize and communicate ideas
Trebuchet	Design and build a trebuchet with plastic pipes, connectors and wood sticks to throw a tennis ball as far as possible.	Sketching annotating brainstorming safety time management
Fanboat	Design and build a fanboat with foam board, fan, motor, rudder, so that the boat would travel forward and turn directions.	Sketching annotation CAD safety, foil design aerodynamics

Marshmallow challenge and foil boat. The marshmallow and foil boat activities are conducted in the same three-hour session. The first part of the session is the marshmallow challenge. This marshmallow challenge was designed to help students identify basic engineering design principles for prototyping and building stable supporting structures. Working in groups of 3-4, the students are given twenty spaghetti sticks, one yard of masking tape, and one yard of string to build a free-standing structure to support a marshmallow. The small groups setting helps to foster collaborative experiences that are applicable across different types of projects in engineering¹⁷. The goal is for the students to create as tall a structure as possible, using as much or as little material as necessary. Following the introduction of the activity, students are given eighteen

minutes to construct their structures. Structure heights are measured at the conclusion of this time period. A debriefing session following this period is used to probe students for their observations, as well as effective strategies of their design processes. For students in Workshop 1, we engaged them in two marshmallow challenge sessions. The first trial was at the beginning of the two-week workshop, while the second was on the 11th day of the workshop, when they have experienced all the design activities, except for finishing the last activity.

The foil boat activity was designed to help students identify factors that influence buoyancy, such as weight distribution and volume, as well as placing emphasis on the importance of early prototyping. Students worked individually for both portions of the activity. For the first portion of the activity, students were given a six by six-inch piece of standard aluminum foil. They were given fifteen minutes to sculpt a foil boat that would hold as many nickels as possible when placed in a tub of water. During this time, the students are encouraged to test their designs and modify their prototypes before the final testing session at the conclusion of the time period. A discussion period is held following the testing of this initial portion to observe effective design strategies in making the foil boats. The second portion of the activity is allotted ten minutes in which students are tasked with holding as many nickels as possible using as little material as they can. Students are allowed to ask for specific amounts of aluminum foil and are given bonus points as they for using smaller portions of foil. A debriefing session follows this activity to help students connect their experiences with the design principles. This session of marshmallow challenge and foil boat lasted for three hours, with short breaks in the middle of the session.

NERF blaster dissection. Students were provided with NERF blasters in order to help them learn how product dissection can inspire design concepts. Students were broken into teams and given one of four blasters. Each blaster had a fundamentally different mechanism to launch the dart: electric pump, air bladder, piston and spring, and plunger and spring. Prior to opening the products, students were instructed to record how they believed the blaster worked. They then opened the devices and compared the device with their predictions. We discussed the various design principles and system connections inside the devices. We also used this activity to practice sketching mechanical designs. This session lasted for three hours, with short breaks in the middle of the session.

Sketching workshop. This activity is designed to help students develop visual thinking skills and understand why sketching is important for engineering. We taught students how sketching can be used to enhance design. This activity alternated between lecture-based instruction and group work. The content was extracted from our prior work exploring which sketching skills and activities are best for designers¹⁸. The first part focused on the nature of sketching and emphasized that sketching does not have to look good to be good. We also used art-based warm-ups to prime the students for receptiveness to sketching. The second part focused on sketching skills including line straightness and thickness and expressiveness. The third part detailed how sketching is used in design to transition from vague, tentative concepts to detailed, well-defined products. Lastly, we emphasized the importance of Boolean shape construction, showing context, showing motion or flows, and annotating sketches. We again reiterated the importance of keeping sketches simple. This session lasted for three hours, with short breaks in the middle of the session.

Trebuchet activity. This activity is broken into two main sections: an hour and forty-five minutes planning and building section, and a final testing section. Before beginning the activity

students are shown short samples of trebuchets in action. This is to alleviate any misconceptions of the trebuchet as it is common to picture a catapult when hearing the word trebuchet. Additionally, it is the first exposure of some students to a trebuchet. The plan and build section begins following this introductory portion. Students work in groups of 3-4. While building, students are also encouraged to apply lever principles and those they learned of structures during the marshmallow challenge. Following the conclusion of the building period, students are taken to an open location for the testing phase, where students use their trebuchets to launch objects (e.g., tennis ball) as far as possible. This session lasted for three hours, with short breaks in the middle of the session.

Fan boat activity. This activity is designed to help students apply the concepts and design principles constructed in the previous two activities, such as designing a stable supporting structure, weight distribution, and identify design principles that enable a fan to move forward and turn the directions of objects. This activity was conducted over the course of four separate sessions, totaling a time of approximately nine hours. The fan boat activity was designed to incorporate the concepts and principles constructed in the previous week's activities. Students continued to work in groups of 3-4, given sheets of foam board, the motor and other electrical components, and large supplies of other various arts and crafts products (e.g. popsicle sticks, string, hot glue, etc.). The only non-standard supply provided to the students were acrylic control horns (a triangle shaped device that connects the parts). These were provided to the students in order to ensure the rigidity and success of such a vital part. With these supplies, students were tasked with building their fan boats to maneuver an obstacle course on a smooth linoleum surface. While building, students are encouraged to apply the principles they learned of structures, weight distribution, energy transfer, and prototyping during their design and build processes. The principles guide the students in understanding the physics required by the fan boat to function, dictating some of the basic elements of their designs without limiting their design freedoms. Student designs were not limited to the preconceptions of the activity facilitators. Following the completion of this final project, students were prompted with discussion to analyze the concepts they used in the design sessions.

At the end of the two-week session, students filled out a self-efficacy survey with the same content as the survey given at the beginning of the session.

Data Analysis

Self-efficacy beliefs. To answer the research question on 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. Students' responses to the self-efficacy surveys are recorded and analyzed using paired sample t-test. Twelve students in Workshop1 and another twelve students in Workshop2 completed both the pre and post self-efficacy surveys (See Table 4).

Design quality. Two raters evaluated the quality of the design outcomes in the Marshmallow Challenge activity first and second trial for students in Workshop1. Using the decision tree, the raters made evaluations based on the following procedure:

- 0 if the design was not functional,
- 2.5 if it was marginally functional,
- 5 if the design was functional, but did not make good use of the physics principles,

- 7.5 if the design used physics principles very effectively, and
- 10 if the design had incorporated physics principles in an unusual or clever way.

The interrater reliability between the raters is 0.995 (Spearman’s rho). The ratings showed that all four teams made improvements from the first to the second Marshmallow Challenge trial, changing from an average of 1.93 among the four teams in the first trial to 8.43 in the second trial (10 as the highest possible score). We selected a team with the highest increase (8.75) and examined their application of design thinking using the video coding protocol.

Application of design concepts. To answer the research question on the influence of the workshop on students’ design concepts, we used the design process coding protocol to analyze students’ design behaviors (the development of the protocol is illustrated in the Measures section). The protocol categorized design behaviors into planning, building and testing phases; within each phase there are three types of behaviors, including verbal/abstract, visual/virtual, and physical/tangible. Two graduate research assistants from engineering and engineering education, who have experience with design and physics conducted the coding using the protocols. To avoid bias, the coders are not involved in the instruction activities of the workshop sessions. We first provided training for the coders and had the coders work on sample videos independently. We checked that the interrater reliability was 0.996 (Spearman’s rho), which was deemed sufficient for the raters to work independently to code the videos. The coders used NVivo software to code the videos and paused to code at each 15 seconds intervals, where they gave the observation a descriptive label using one of the categories in the protocol. In order to identify the changes in design thinking for students who improved their design qualities, we examined the group of students with the highest increase in design quality from Marshmallow Challenge trial 1 to trial 2 in Workshop1. Using NVivo, we generated graphs to visually present the students’ design behaviors throughout the sessions.

Results

Development in Self-efficacy Beliefs

Using paired sample t-test, we found that students’ self-efficacy beliefs in engineering sketching, design, prototyping, and collaboration changed significantly from before to after attending the workshop. Specifically, for participants who attended the first session Workshop1, the self-efficacy ratings increased significantly from pre to post-survey, $t(11)=3.93$, $p=.002$, Cohen’s $d=2.37$. For participants who attended the second session Workshop2, the self-efficacy rating increased significantly from pre to post-survey, $t(11)=5.19$, $p<.001$, Cohen’s $d=3.13$. See table 4 for descriptive statistics for the self-efficacy survey responses.

Table 4

Descriptive Statistics for Self-efficacy Survey Responses

	Pre-survey			Post-survey		
	n	Mean	SD	n	Mean	SD
Workshop1	12	95.75	10.19	12	103.00	8.41
Workshop2	12	98.17	11.167	12	112.25	10.69

Applying Design Concepts in Engineering Design Processes

Students in Workshop1 had two attempts at designing the marshmallow tower: the first attempt was on the first day of the two-week workshop. Students were given 30 minutes to work on the problem. At the end of the first attempt, the students received a short lecture on basic trusses, specifically the advantage of building in triangular frames, along with real-world examples of structures based on triangular frames. Students were not told that they will work on the Marshmallow challenge again, but were encouraged to think about what they learned from this activity and apply in the future. More than a week after the first marshmallow challenge, when students have had nine days of different types of design activities and have started working on the last activity of the workshop—building a fan boat, the students engaged in a second Marshmallow challenge. The second attempt was similar to the first, except that it was 20 minutes long.

Using the coding scheme described in Table 2 in the Measures section, the design activities were coded using the coding protocol, and categorized students' behaviors into “modality+activity” types (e.g. verbal planning, tangible building).

Figure 2 shows the coded timeline of a team performing the marshmallow tower design activity, combining the categories into the overarching themes of *plan*, *build* and *test*. In the first trial: the team spent most of their early efforts in planning, and later moving on to building, continuing to switch between building and testing, with some movement back into planning. In total, the team spent 30% of their total time planning, 46% of their time building, and 11% on testing. This contrasts with their second trial, where they spend only 11% of time planning, 13% of time testing, and 76% of time in building. In addition, the students transitioned from planning into building much earlier in the second trial than the first trial. The rate at which the team switched between activities remained similar: 1.26 times a minute on average for the first trial, and 1.15 times a minute for the second trial.

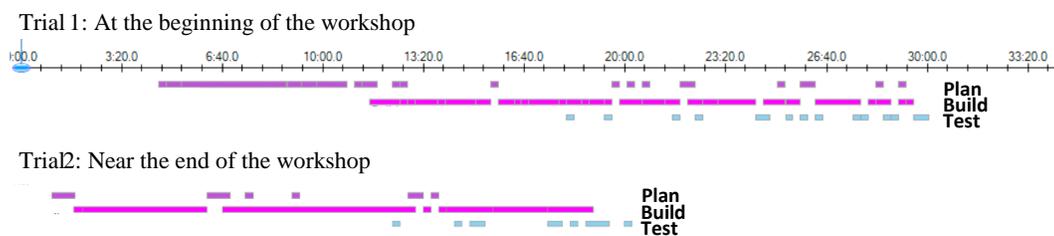


Figure 2: The coded timelines of one design team showing the activities of planning, building, and testing during the marshmallow tower design challenge at the beginning and near the end of the workshop.

We also examined students' behaviors using the “modality+activity” types (e.g. verbal planning, tangible building). As is demonstrated in Figure 3, students made quicker transition from planning into building in trial 2 when compared to trial 1. Besides, students increased in the percentage of time spent on tangible planning (2.2%), verbal building (11.99%), and tangible building (29.09%), but decreased in the percentage of time spent on verbal (10.65%) and visual planning (10.4%) (Figure 3). Thus, while the students spent time on planning in both trial 1 and trial 2, they showed the tendency to use more tangible planning with objects, rather than mainly using verbal and visual planning.

Trial 1



Trial 2

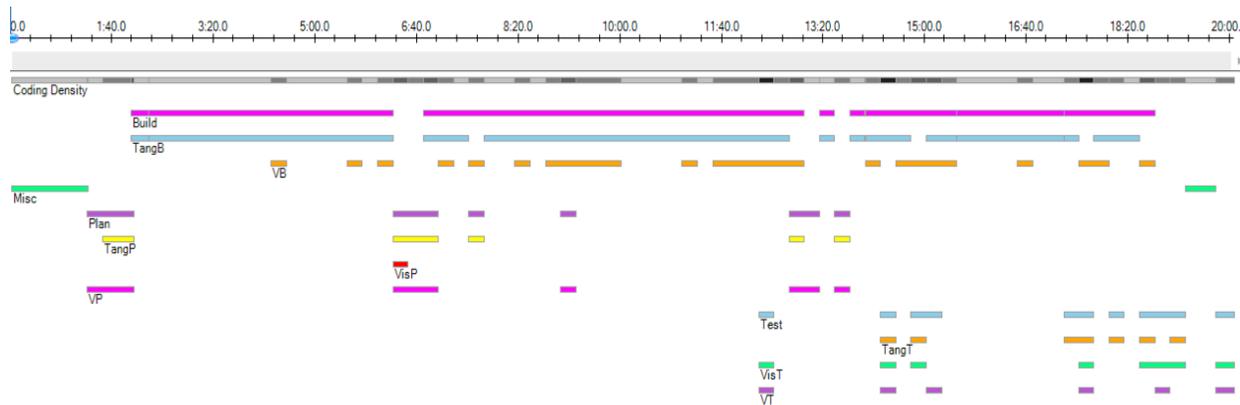


Figure 3: The coded timelines of design team showing the design activities in modality+activity modes during the marshmallow tower challenge at the beginning and near the end of the workshop. The horizontal line on the top represents the lapse of time. VP=verbal planning, VisP=visual planning, TangP=tangible planning; VB=verbal building, TangB=tangible building; VT=verbal testing, VisT=visual testing, TangT=tangible testing.

Discussion

This study contributes to literature on middle school students' development of design concepts by showing that after attending a workshop focused on design and making, students' self-efficacy beliefs increased significantly. In contrast with previous studies that only focused on students' development on science concepts, this study demonstrated instructional modules that can be adopted to foster students' self-efficacy beliefs and knowledge directly related to engineering design and making, and applying physics concepts in design context. In addition, this study developed an analysis protocol for identifying design behaviors, allowing researchers to examine students' development in design concepts and how students conduct the design process.

Effect of Toy Design Workshop on Self-efficacy

Findings from this study suggest that participants' self-efficacy in sketching, prototyping, designing and collaboration improved significantly from attending the toy design workshop. This finding builds on previous study by showing that engaging students in hands-on design tasks is beneficial for the development of self-efficacy beliefs. Although previous study has suggested that involving students in engineering-related activities is helpful for enhancing students self-efficacy in engineering as a discipline in general¹⁹, this study demonstrates the advantages of using hands-on engineering design activities in increasing self-efficacy in engineering sketching, prototyping, designing, and collaboration.

Drawing from social cognitive theories that identified the sources self-efficacy beliefs and the empirical evidence on sources of engineering students' self-efficacy beliefs^{9,20}, participants in the current workshop may have developed self-efficacy beliefs through experiences that promoted their mastery experience, vicarious experience, physiological state, and social persuasion.

For mastery experience, we provided students with a material-rich design environment, and engaged students in hands-on design activities that encourage them to go through the design cycles involved in engineering design. Such activities allow students to experientially learn about the processes in engineering design. In contrast with more advanced engineering design activities, such toy design activity is especially beneficial for its relatively low requirement on disciplinary knowledge to participate, where every student can contribute in some way to the making process regardless of their prior knowledge and skills. Besides, because the activities are set up in a way to encourage students' focus on process rather than outcomes, students are more likely to gain in mastery experience for the activities are focused on mastery-oriented goals.

For vicarious experience, students were grouped into small design teams, where they can collaborate and observe peers in designing and making objects. There were also more advanced undergraduate and graduate mechanical engineering students leading and assisting the workshop sessions, who can also serve as models for the participants in adopting designer-like thinking and mindsets. The benefits of having students work in group comes also helps with the situations when individual students feel stuck and they can look to other individuals in the group for ideas and alternative solutions. This type of peer teaching not only provides support for individual students, but also provides vicarious experiences that by seeing peers' effort and contributions, allowing observers to develop the belief that they can accomplish the same type of design tasks.

Development of Design Concepts in Design Process

We demonstrated that students with increased design quality ratings allocated time in the plan-build-test design process differently after attending the two-week workshop and engaged in various hands-on design activities. Specifically, the students showed the tendency to apply more tangible planning and building, by interacting with physical objects. This finding is consistent with results from previous research on design thinking: as students gained experience with design, they tend to allocate time differently for the different stages in the design process¹⁴. In our study, compared to the first trial at the beginning of the workshop, students transitioned from planning to building design ideas earlier in the second trial. Specifically, students devoted more time to design activities related to tangible/physical aspects in planning and building, similar to prototyping in engineering settings. Students also resorted less to verbal or visual planning and building. These

shifts in design behaviors may reflect changes in student's mindset about engineering design: realizing the importance of using tangible materials to prototype early in the design process. As previous research has suggested, prototyping early or prototyping to think is a crucial element in design, which facilitates students' embodied cognition in material context and later engineering design practices^{21,22}. Such change in the design process can be attributed to students gaining insights into the underlying physics concepts, as well as the design concepts. Considering that in between the first and second trial, the students have engaged in several hands-on design activities, where they developed understanding in trusses and the structural merits of triangular frames, the results suggest the potential of such toy design workshop in promoting students' concepts about engineering design.

Future Directions

Future studies should explore the influence of more open-ended design tasks on students' development in design thinking and self-efficacy, and investigate how students apply engineering design concepts in the engineering design and making process.

Limitations

This study has limitations in sampling and implementation of the procedures. A limitation in sampling is that participants self-selected to attend the toy design workshop, which may imply that the participants have strong interest in design and making. As a result, the sample in this study may not represent populations whose interest is not aligned with the goals of this workshop. Another limitation in this study is that the duration of the workshop was two-weeks. Given more time, students may have demonstrated more prominent changes in attitudes and conceptual understanding in physics and design. Thus, cautions need to be taken when generalizing the results from this study.

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