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Examining Middle School Students' Engineering Design Processes in a Design Workshop

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Abstract

Design thinking has an important role in STEM education. However, there has been limited research on how students engage in various modalities throughout the design process in hands-on design tasks. To promote middle school students' engineering literacy, it is necessary to examine the use of design modalities during design. Using a case study approach, we examine middle school students' design stages and modalities during design activities. We also identify the patterns of design processes in the teams with different design outcomes. Drawing on theories in design thinking and embodied interaction, we proposed a framework and devised a video analysis protocol to examine students' design stages and modalities. Middle school students attending a design workshop engaged in two design activities in teams of 3–4 people. The design sessions were video recorded and analyzed using the video analysis protocol. The teams engaged in the stages of planning, building, and testing, while employing the verbal, the visual, and the physical modalities. The teams that varied in design outcomes exhibited different patterns in the use of multiple modalities during the design stages. This study contributes to research on design thinking by proposing a framework for analyzing middle school students' multimodal design processes and presenting data visualization methods to identify patterns in design stages and modalities. The findings suggest the necessity to examine students' use of design modalities in the context of design stages and imply the potential benefits of using multiple modalities during design. The implications for future research and education practices are also discussed.

Keywords Engineering design · Design thinking · Middle school · Design processes

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Introduction

In the United States, developing middle school students' engineering design thinking is an important learning objective that has been highlighted in the Next Generation Science Standards (NGSS Lead States 2013). The push for adding engineering design to the NGSS and introducing students to engineering as early as in elementary school has been motivated by the increasing demand for STEM professionals (Committee on STEM Education 2018; U.S. Department of Education 2015). In addition, participation in precollegiate STEM educational experiences is associated with adult accomplishments in STEM areas and the enhancements of such fundamental thinking skills as design thinking (Wai, Lubinski, Benbow, & Steiger, 2010). Thus, exposing middle school students to engineering design can help to promote the engineering education pipeline and the development of design thinking skills.

As a process predominantly situated in the material context, engineering design thinking often involves multiple modalities, such as verbalizing new design ideas through speech while manipulating tangible materials in the physical environment (Dorst 2004; Johri and Olds 2011; Moore et al. 2013). However, such multimodal processes have been found lacking in traditional classroom activities using abstract operations and limited types of modalities (Johri and Olds 2011; Moore et al. 2013; Razzouk and Shute 2012), which may create challenges for students to solve design problems effectively and by extension difficulties in sustaining the engineering education pipeline (Dorst 2004; 2015).

Previous research in developmental psychology has shown that early adolescence, which spans across middle school, is a critical period for the formation of neuronal connections governing problem-solving strategies through specialized learning experiences (Kuhn 2006). Thus, it is necessary to provide specialized learning experiences that have been found to facilitate the development of design thinking, including solving hands-on design problems and engaging in the multimodal design processes for middle school students (Mentzer et al. 2015; Razzouk and Shute 2012; Simpson et al. 2017), to transform their "habit of the mind"—from fixating on limited types of modalities towards actively adopting a wide variety of modalities during design (Neroni et al. 2017). However, there has been limited research on how middle school students engage in various modalities throughout the design process in hands-on design tasks (Simpson et al. 2017; Walkington et al. 2014). In this study, we developed a framework to examine the stages and modalities of middle school students' design thinking processes during hands-on design activities.

We build on previous research in this area and address the following research questions:

1. What are the patterns of multimodal design processes across time during middle school students' engineering design activities?
2. What are the patterns of the design stages and modalities in teams with different design outcomes?

Theoretical Background

The Stages and Modalities of Design Thinking

There exist a variety of views on the definition of design thinking. One common definition views design thinking as a nonlinear and iterative cognitive process, where designers go through cycles of identifying problems, building prototypes, iteratively modifying prototypes, and communicating design solutions (Dym et al. 2005; Razzouk and Shute 2012). While such definitions highlight the processes related to inquiry and learning, systems thinking, and collaboration (Dym et al. 2005), design thinking has also been defined from the users' perspective. For example, Brown and Wyatt (2015) defined design thinking as user centered and encompassing the inspiration, ideation, and implementation spaces, where the designers engage in rapid prototyping and loop back through the different design spaces to address the users' needs. Although such user-centered definition revolves around the centrality of the users' needs in the design thinking process, it still suggests an underlying cycle of processual stages that designers need to traverse through in solving design problems. In this study, we choose to focus on the stage dimension of design thinking, which emphasizes the processes related to "experiment, create and prototype models, gather feedback, and redesign" stages (Razzouk and Shute 2012, p. 330).

Design Stages Despite the importance of design thinking, its application is not intuitive and needs early and prolonged exposures starting in elementary or secondary school levels (Walkington et al. 2014). In the US, where this study was conducted, engineering as a subject area has not typically been addressed in middle school; in fact, most students would not have exposure to engineering or engineering design until college (for those who select engineering majors). Thus, introducing engineering design concepts in middle school, which is part of secondary education in the US, provides early exposure for students. However, research on how middle school students approach design problems and engage in design thinking processes that involve tangible objects has been limited. Existing research has focused on think-aloud design tasks, where the students talked about the design processes rather than creating a tangible design product. For instance, Mentzer et al. (2015) compared high school students' verbal protocols with that of expert engineers during design think-aloud tasks. The results showed that the high school students went through three major stages in design: problem-scoping, developing alternative solutions, and project realization. Besides, high school students with less experience in design spent significantly less time than more advanced students and experts on information gathering during the problem-scoping stage as well as the idea generation and the feasibility analysis/evaluation during the developing alternative solutions stage. Such results have provided insights into the design thinking processes and highlighted the value of examining how students distribute time among the design thinking stages. However, because design processes are often multimodal in nature and utilize a variety of verbal and nonverbal modalities (Nathan et al. 2013; Walkington et al. 2014), we need to also examine how students engage in different modalities during design.

Design Modalities Recent research has begun to examine the modalities of students' design process. For example, Mentzer et al. (2014) analyzed high school students' verbal protocols during design think-aloud tasks, where the students described the processes of solving design problems. The findings from this study showed that the high school students tend to emphasize graphical modeling (e.g., creating pictorial objects, such as sketches), while making few references to mathematical (e.g., describing the mathematics of the design features, such as using math formulas to quantify certain aspects of the design) and physical modeling (e.g., creating actual objects in the physical environment, such as building models of things). Thus, Mentzer et al. suggested that the imbalance in how the students adopt the different modalities may prevent the students from obtaining favorable design outcomes. Along this line of research, several studies (e.g., de Vries 2006; Moore et al. 2013) have shown that engaging in multiple modalities is important to the design process: it can *complement* design by providing different types of information; *constrain* design by specifying the conditions of design artifacts to reduce the ambiguity and uncertainty in interpretation; and *construct* design by facilitating the process of deeper understanding (Ainsworth 1999; de Vries 2006). Moreover, students' ability to switch modalities, such as switching between the graphic and the physical modality, suggests a deep level of conceptual understanding (de Vries 2006). Therefore, we need to examine how students engage in and switch among the various modalities in the engineering design process.

In addition to the physical and graphical modalities, the verbal modality is crucial to the design process, especially in collaborative design settings. However, it is important to note that the verbal modality is often accompanied by other modalities in hands-on design tasks, which often involve the verbal interaction among people as well as the nonverbal interaction between people and objects (Brereton 2004; Dong 2007; Purzer 2011). Consider a common design scenario where a group member physically manipulates objects while telling the group that they should get "this" object to stand on top of "that" object. Here, the design idea is conveyed through the verbal interaction among group members, and equally if not more prevalently through the speakers' physical interaction with the objects. As the design idea is formed and encapsulated in words on the mental plane, the representation of a promising solution is portrayed and developed through the bodily interaction with objects on the physical plane (Howard et al. 2008; Roth 1996).

In summary, the foregoing studies identified that students tend to adopt the physical, graphical, and verbal modalities during design. Although this previous research mainly used verbal protocol analysis to examine the modalities that the students use while talking about the design process (i.e., design think-aloud), the findings suggest that it is necessary to investigate how students transition through the major design phases and examine the use of modalities. In the current study, the students worked on hands-on design tasks that led to tangible design products. Therefore, the nonverbal modalities (e.g., graphical modality, physical modality) are especially important because, on the one hand, the students had access to physical objects and the options to visually examine and sketch the objects; and on the other hand, theories in design thinking have highlighted the value of embodied cognition (Howard et al. 2008; Suchman 2000), which involves using concrete objects to build prototypes and guide design thinking. Building on the modalities proposed in previous studies, which served as the basis and point of departure for our protocol development, we developed a video analysis protocol to identify the modalities exhibited by middle school students during the design activities involving embodied processes.

Design Thinking Through Modalities Involving Embodied Processes

Distinct from entirely abstract cognitive processes, engineering design is predominantly situated in the physical environment and embodied in the concrete objects and tangible materials (Johri and Olds 2011). Thus, to learn about design thinking, students need to interact with the physical environment and create visual and physical representations using sketches, gestures, or concrete prototypes (Fish and Scrivener 1990; Mentzer et al. 2014). Therefore, embodied cognition, the concept that cognitive processes are not just carried out in our head, but are also manifested through bodily interactions with the physical environment, has important implications for engineering design (Howard et al. 2008; Suchman 2000).

Integrating embodied cognition in the design process involves adopting the mindset that abstract mental operations can be off-loaded to concrete processes, often manifested externally as using concrete objects in prototyping, or internally as forming imagery representations for design ideas (Wilson 2002). Concrete objects and visual representations facilitate the design process by providing a workable medium that can be used to reduce cognitive load and shed light on new design possibilities (Suchman 2000). However, the traditional abstract classroom activities, which predominantly use abstract representations to promote conceptual understanding, could predispose students to use abstract symbols to construct knowledge about the world and solve engineering design problems. Consequently, students may ignore the necessity of building concrete prototypes in conjunction with mental design ideation (Roth 1996). Engineering design activities that encourage embodied interactions can challenge such a mindset and help students off-load abstract design thinking to concrete design processes. For instance, previous research has suggested that students' physical interaction with the tools and objects can provide the platform for embodied cognition and facilitate engineering design (Carlson et al. 1999). In one study (Roth 1996), fourth and fifth-grade students who began the design process with a formula-based approach were found to generate innovative ideas that diverged from the original plan once they started interacting with the design artifacts. The students also explained, while reflecting on the design process, that the new design ideas emerged as they manipulated the objects in different ways and kept working with the artifacts. This study demonstrated that physically interacting with objects in the planning and building processes allowed students to develop new design ideas that could not be conceived through mental planning alone. Or as Kirsh (2013) described "handling an object, for example, may be part of a thinking process, if we move it around in a way that lets us appreciate an idea from a new point of view." (p. 3:2). Such results emphasize the importance of encouraging students to go beyond mental planning and integrate embodied cognition through "thinking and acting" in the design process (Roth 1996).

Embodied cognition views bodily interactions as an integral part of cognition, where the body either constrains, distributes, or regulates cognitive processes (Clark 2009; Suchman 2000; Wilson 2002). In the current study, we chose to focus on the "body as a distributor" function of the cognitive processes, where the students distribute their design thinking to different modalities that connect the body with the physical environment, such as physically manipulating the objects to prototype, or visually examining the objects as well as creating sketches to represent design ideas.

In summary, students' design thinking should be examined from the design stage and the modality dimensions. Previous research has proposed ways to examine the design thinking processes of experienced engineering students in design think-aloud tasks (Atman et al. 2007). In this study, it is necessary to develop new frameworks appropriate for examining middle school students' design processes in hands-on tasks. Therefore, drawing on theories in design thinking and embodied interaction (e.g., Dym et al. 2005; Dym et al. 2009; Razzouk and Shute 2012; Suchman 2000; Vanasupa et al. 2009), we developed a framework to examine the middle school students' design processes from the design stage and design modality dimensions. The design stage dimension provides insights into how students navigate through the design process of generating design ideas, building prototypes, and testing designs. The modality dimension allows us to understand how students engage in design behaviors in different modalities during the design process. We also explored the patterns of design stages and dimensions in teams with different design outcomes.

Design Outcomes

Previous research has identified the associations between design processes and design outcomes. For example, Sobek and Jain (2007) found that the time spent on system level design processes contribute positively to the quality of students' design outcomes. In this study, rather than identify the causal relationships between design processes and design outcomes, we intend to examine the patterns of design stages and modalities in teams with different design outcomes.

Design outcomes in the forms of tangible artifacts or representations can be evaluated to gain insights into students' design processes. However, many of the existing criteria for design evaluation in engineering education settings tend to focus on design processes rather than the actual outcomes of design (Sobek and Jain 2007). For example, previous research has evaluated the generation of design ideas (Shah and Smith 2003) and design documentation (Westmoreland et al. 2011) based on the criteria of quantity, novelty (McKoy et al. 2001), variety (Hernandez et al. 2013), complexity (McGown et al. 1998), and accuracy (McKoy et al. 2001).

In the limited research that has examined students' design outcomes or products, researchers have focused on the dimensions of design requirements, feasibility, creativity, and simplicity (Hathcock et al. 2015; Sobek and Jain 2007). For instance, Kudrowitz and Wallace (2013) developed a metric to evaluate design sketches and used novelty, usefulness, and feasibility as the main criteria. In summary, previous work on design outcome evaluation has frequently focused on the *quality* dimension by assessing the functionality, the usefulness, and the feasibility of the design products; and on the *novelty* dimension by assessing whether the design products demonstrated novel ideas and innovative solutions. However, these existing studies were conducted with post-secondary students or engineering professionals (Kudrowitz and Wallace 2013; McKoy et al. 2001). There has been a lack of research on evaluating design outcomes for younger students, such as middle school students.

In the current study, we chose to examine middle school students' design outcomes from the *novelty* (e.g., original ideas or innovative solutions) and *quality* (e.g., functionality) dimensions. Understanding the novelty of students' design allows educators to foster the creativity embedded in students' design outcomes, which is an important goal of engineering education—to inspire interest and nurture creativity among engineering designers and thinkers (Brophy et al. 2008). The literature on creativity has considered novelty as a crucial construct and included novelty in a variety of creativity measures (Cropley and Cropley 2005; Sarkar and Chakrabarti 2011). The criteria that previous research has used to assess the novelty of design include the uniqueness and the repeatability of ideas (Demirkan and Afacan 2012; Sarkar and Chakrabarti 2011). In this study, we define the novelty scale as measuring the degree to which design products are novel compared to other designs and the likelihood of being repeated in similar situations.

Regarding the quality dimension, whether a design product can function as intended has been considered as a crucial quality indicator of engineering design outcomes (Pahl et al. 2007; Sobek and Jain 2007). Therefore, it is important to identify whether the students' design outcomes achieved functionality. In addition, considering the important role of physics principles in the functionality of engineering design (McPherson 2010), we define the quality dimension as the degree to which design products are functional and reflect the effective use of physics principles.

The design outcome evaluation tools used in the current study were in the form of decision trees, to simulate industry practices and to help identify the reasons for disagreement among the raters (Booth et al. 2015). In addition, the decision trees were developed to cater to younger students' design activities and can be adapted for use in other educational settings involving middle school students' designing and making.

Methods

Participants

Participants were enrolled in a 2-week Toy Design Workshop held at a university in the Midwest of the United States. The purpose of the design workshop was to help middle school students understand engineering design processes and concepts. The participants self-selected to attend the workshop. This sample was selected because the participants completed various design activities from scratch to finish daily during the 2-week workshop, which allowed for in-depth observation and analysis of the design processes. Twenty-seven students between 13 and 14 years old participated in the Toy Design Workshop. The participants are from various racial/ethnic backgrounds: 7.41% were African American, 44.44% were Asian, 3.70% were Hispanic, 22.22% were Native American, and 22.22% were White. Before each design activity, the participants were surveyed verbally on whether they have engaged in the activities before. None of the participants indicated that they have previously participated in the design activities presented in the workshop.

As shown in Table 1, in each activity there were eight design teams (3–4 students in each team). During data analysis, we focused on a subset of teams in each activity due to factors beyond our control (i.e., technical issues with the recording devices): six teams in the marshmallow tower activity and seven teams in the trebuchet design activity were included in the analysis. To simulate real classroom activities, the team member compositions were the result of voluntary choices rather than a random assignment. Because we allowed the students to choose the teams to join, the team members varied across the two activities (i.e., students in Team 1 of the marshmallow tower activity were different from the students in Team A of the trebuchet activity). Besides, the gender composition is homogeneous for some teams, as students in this age group have the tendency to work with peers of the same gender and chose to join teams with students of the same gender (Mehta and Strough 2010).

Procedures

The workshop space was set up in a way to promote collaboration within the team and provide hands-on design environment. Large work benches were set up in the middle of the room, with cabinets and whiteboards on both sides of the room to serve as additional workstations. To allow for video recordings of the design sessions, GoPro cameras were set up on the top of the cabinets facing the work benches and were adjusted to the right angles to capture the design teams' behaviors. In addition, audio recording devices were placed in the center of each work bench to record the teams' voices. After the design sessions, the video and audio recordings were synced according to the time stamps to serve as the video data for the analysis. One

Table 1 Participants in the teams of the marshmallow tower and trebuchet activity

Activity	Team	*n*	Male	Female
Marshmallow tower				
	Team 1	3	1	2
	Team 2	4	1	3
	Team 3*	4	4	0
	Team 4	3	3	0
	Team 5*	3	3	0
	Team 6	4	4	0
	Team 7	3	3	0
	Team 8	3	0	3
Trebuchet				
	Team A	4	2	2
	Team B*	3	0	3
	Team C	3	3	0
	Team D	4	4	0
	Team E	3	0	3
	Team F	4	4	0
	Team G	3	3	0
	Team H	3	3	0

*Teams 3 and 5 in the marshmallow activity and team B in the trebuchet activity were not included in the qualitative analysis due to factors beyond our control (i.e., technical issues with the recording devices)

instructor and four to five assistants, from undergraduate and graduate levels in mechanical engineering, were available to interact with the students.

On each day of the 2-week workshop, the participants engaged in one of a series of design activities including the marshmallow tower challenge and foil boat activity, NERF blaster dissection, the trebuchet activity, and the fan boat activity in small groups (three to four students) for 3 h, with two to three 10-min breaks during the session (for full descriptions of the activities and the rationale for selecting these activities, see Zhou et al. 2017). The marshmallow tower and trebuchet activities were selected as the focus of analysis for this study because they required students to progress through the design process and were each completed in one design session—an appropriate duration for video analysis; and students generated observable design products from these two activities. The hands-on design tasks similar to the ones used in this study have also been used in previous research due to being easy to implement, low cost, and design focused features (English et al. 2013; Hennessey and Johnson 2010). However, the previous studies that have used similar activities had different purposes than studying design thinking, such as promoting STEM education outreach (Hennessey and Johnson 2010) or students' reflections about simple machines in design (English et al. 2013). In this study, we used these activities as the platforms to examine the design thinking processes of middle school students in hands-on design environment involving interaction with physical objects and resulted in tangible design products.

After introducing the activities in each of the two design sessions, the instructors conducted a verbal survey with the students and inquired if they have done the activity previously. None of the students responded that they engaged in the marshmallow tower or the trebuchet activities before participating in the workshop.

In the marshmallow tower activity, students first learned about the principles of designing and building a solid supporting structure. The instructors introduced such principles by showing examples in real-life settings and facilitated students' discussions of the principles, such as the advantages of using triangle shapes to strengthen the base or the structure. The examples used for introducing the physics principles were not the same as the marshmallow tower design activity. Then, the students worked in small groups to design the tallest freestanding structure and balance a marshmallow on top. This activity took approximately 20–30 min. In this activity, the students were provided with a bag of supplies with 20 spaghetti sticks, 1 yard of masking tape, and 1 yard of string (see Zhou et al. 2017 for more details about the activity).

In the trebuchet activity, the students started with reviewing the principles that they discussed previously in the marshmallow activity and the instructors facilitated a discussion to help the students reflect on the importance of a solid structure in designing and building. The instructors also introduced the lever principle by demonstrating a simulation game where the students manipulated the distance of a fulcrum to the mass and the weights at the two ends of a lever to balance the lever. After the simulation game, the instructors facilitated discussions about the basic lever principles, such as the importance of considering the distance between the pivot point, the projectile, and the weight. The examples used for introducing the physics principles were not the same as the trebuchet design activity. Then, the students worked in small groups of three to four to build a trebuchet that threw an object for a distance. In this activity, the participants were provided with plastic pipes, wood sticks, small plastic bags, and connectors for connecting the pipes. This activity took approximately 1.5 h (see Zhou et al. 2017 for more details about the activity). Both the marshmallow tower and the trebuchet design sessions were video recorded to facilitate the analysis of the students' design behaviors during the activities.

Instruments

Video Analysis Protocol Drawing on theories in design thinking and embodied cognition (i.e., cognitive processes are not just conducted through mental operations, but are also distributed in the bodily interactions with the physical environment) discussed previously in the "Theoretical Background" section, we followed the cyclical analytical processes of video data suggested in previous research (Jacobs et al. 1999) and developed a video analysis protocol for the middle school students' design processes. As Jacobs et al. (1999) suggested, video data allows for an iterative coding process involves watching and discussing the videos, developing and applying codes, analyzing and linking the codes back to the video, and iteratively revising the codes. Following this procedure, four researchers in mechanical engineering and education watched and discussed several video segments that were randomly selected from the beginning, middle, and the end of the activities (i.e., using random number generators to pick the videos). The four researchers developed the codes for the videos independently. Following observation methods reported in previous studies, the researchers watched the video for 15 s and paused the video to analyze the conversations, behaviors, and interactions among the team members to generate descriptive codes for the 15-s segment (Deckner et al. 2006; Powell et al. 2008). This process continued until the selected segments were completed.

While developing the coding scheme, the researchers refined the operational definitions of the codes by consulting coding schemes proposed in previous studies that highlighted the stages and modalities of engineering design processes, and modified the codes to fit the context of this study (Atman et al. 2008; Dym et al. 2005; Mentzer et al. 2014; Purzer 2011). After independently coding the selected video segments, the researchers discussed as a group and revised/consolidated the coding categories (MacQueen et al. 2008; MacQueen et al. 1998).

During the code development process, the researchers clarified instances of students' behaviors that may raise ambiguity for the codes. For example, the "Visual Build" code was generated to refer to instances where the students utilized digital tools to build models, such as using computer-aided design (CAD) software. However, a question emerged in the code development process regarding whether a participant's sketching on paper on how to build a component of the design should be coded as "Visual Plan," or "Visual Build." The researchers discussed this issue and identified the distinction that when students sketched on paper, they are not able to create the level of details and complete models that equate to the building of a design, which is the case in CAD design as the CAD model can be used directly for producing the final design product in 3D printing or other platform. As a result, the researchers resolved to categorize students' sketching on paper to build a component as visual planning rather than visual building. The researchers also specified that in the context of the activities in this study, instances of visual building are mainly CAD modeling, which is an available option for the students if they choose.

The code development process repeated several iterations resulting in coding categories describing the design process: *planning*, *building*, and *testing*; and the modalities of the design behaviors: *verbal*, *visual*, and *physical.* As a result, there are nine design behavior categories: *verbal planning*, *visual planning*, *physical planning*, *verbal building*, *visual building*, *physical building*, *verbal testing*, *visual testing*, and *physical testing.* Table 2 includes the definitions of each of the codes and examples.

In previous research, students' design stages have been examined from the cognitive and communicative dimensions, such as identifying problem scope, finding and choosing

Table 2 Analysis protocol of the design processes and modalities

Modality	Design process					
	Plan		Build		Test	
	Definition	Example	Definition	Example	Definition	Example
Verbal[a]	Discuss the design problem or potential design ideas	"We should have a sturdy base."	Discuss ways of combining materials and building the structure, or describe the procedures/actions involved in building	"Where is the tape? Tie the tape here."	Discuss the performance of the prototypes or design outcomes	"It is not holding together."
Visual	Create sketches of design ideas or visually examine design materials to generate design ideas	Sketch the front view of a tower in a notebook during planning	Model design ideas in a CAD (computer-aided design) software	N/A[b]	Visual inspection of the performance of the prototypes or design outcomes	Observe the performance of the freestanding tower
Physical	Without fixating the materials, physically interact with and manipulate design materials to facilitate design idea generation	Plan the base of a structure by putting several sticks together (without taping or fixating) to form an "A" shape	Combine and fixate the materials in a certain position, or orientation	Students combine the sticks with tapes to build the base of the tower	Apply force/weight to test the performance of the design	Place the marshmallow on the top of the tower and see if the structure would stand or fall

[a] Apply only to peer-peer interactions rather than facilitator-student interactions

[b] Visual building is not observed in the activities in the current study because the tasks do not require the use of visual building such as using CAD software to build design products

solutions, or communicating design ideas, through the use of think-aloud verbal interview protocols with high school and undergraduate students (Atman et al. 2008; Mentzer et al. 2015). While the internal cognitive and communicative processes are very important findings, in this study, we focused examining the stages of plan, build, and test, which are behavioral dimensions that are observable through video recordings of students in natural settings without being interrupted or interviewed in the middle of a design session. We intend to use the findings from this study to inform future research that examine in more detail about the internal cognitive and communicative processes.

The Design Outcome Scales To assess design outcome, we chose to focus on the *quality* and *novelty* aspects of the design products based on our previous work (Booth et al. 2016), and the criteria proposed in previous research (Kudrowitz and Wallace 2013; McKoy et al. 2001). The rationale for selecting these criteria is also discussed in the design outcome of the "Theoretical Background" section. The scales are in the format of decision trees, which simulate industry practices and help to identify the reasons for disagreement among the raters (Booth et al. 2015).

The Design Quality Scale As shown in Fig. 1, the scale evaluates design quality by considering a decision tree—a sequence of criteria on the *functionality*, the *basic use of physics principles* in design, and the *effective use of physics principles* in design.

The first criteria in the decision tree asks the evaluator to assess the functionality of the design and asks "Is the design functional?" Here, the evaluator determines whether the design met the design goals (i.e., support the marshmallow on the top of a freestanding tower in the marshmallow activity; throw the object at a distance in the trebuchet activity). It is also important to note that although the height of the tower is an important factor in the marshmallow activity, the actual height of the students' towers was not used as a factor for evaluating the functionality of the design. This is because the students can build a tall tower with low level of functionality, such as having an unstable structure. Therefore, we focused on the stability of the towers rather than the height during the functionality evaluation. Also, the height of the tower outcome is embedded in the second and third criteria where the students' use of the physics principles contributes to the height of the tower. The evaluator proceeds to evaluate the second criteria if the response to the functionality criteria is "Yes"; and the evaluator may assign a score of 0 or 2.5 if the response is No or Marginal. Marginal refers to situations when the students' design has shown minor issues that prevent them from fully meeting the design goals (i.e., the tower is freestanding while supporting the marshmallow on top, but the structure appears to be wobbly and unstable).

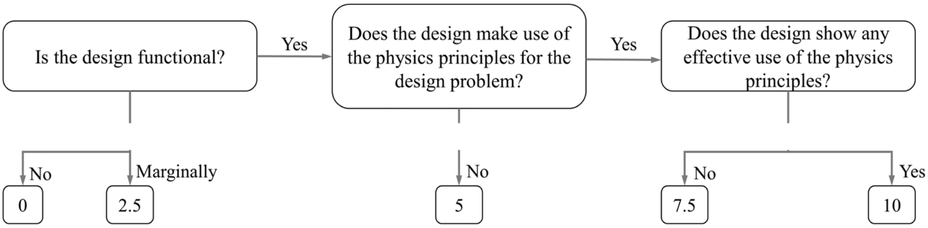


Fig. 1 Design quality rating scale in the decision tree format. The evaluation process navigated from the leftmost to the rightmost criterion. The evaluation resulted in 0 if the design was not functional, 2.5 if it was marginally functional (e.g., a freestanding but wobbly and unstable structure), 5 if the design was functional, but without the use of the physics principles, 7.5 if the design showed basic use the physics principles, and 10 if the design used the physics principles effectively to achieve the design goal

The second criteria in the decision tree asks, "Does the design make use of the physics principles for the design problem?", where the evaluator determines if the design shows the basic use of physics principles. Because the participants are middle school students whose knowledge in physics is still limited, the evaluation of the use of physics principles focused on whether the design integrated the key principles introduced in the workshop (e.g., the importance of a stable supporting structure and the strengths of triangle shapes for the marshmallow activity; and using lever principles to lift objects in the trebuchet activity) rather than the students' general knowledge in physics (for a description of the physics principles introduced for each activity in the workshop, see Zhou et al. 2017). The *basic use of the principles* criteria is met when the students showed consideration of at least one principle (e.g., the design included features to strengthen the base of the marshmallow tower). The evaluator proceeds to the third criteria if the response to the basic use of physics principles criteria is "Yes," or assigns a score of 5 if the response is "No." The third criteria asks, "Does the design show any effective use of the physics principles?", where the evaluator determines if the design has integrated the physics principles in an effective way to meet the design goals (e.g., adding triangle shapes at the bottom, the middle, and the top of the tower to strengthen the structure, which resulted in a tall tower). The evaluator assigns a score of 7.5 to the design if the design showed no effective integration of physics principles, or a score of 10 if the design has used physics principles effectively to achieve the design goals.

The Design Novelty Scale As shown in Fig. 2, this scale evaluates design novelty by considering a sequence of criteria, including the uniqueness of the design features, whether the unique features improve the efficiency of the system, and whether the unique features are repeatable.

The first criteria asks, "Does the design include unique features?", where the evaluator determines the uniqueness of the design features by making peer comparisons with the other teams' design. Such peer comparison has been used frequently as a novelty measure in the creativity research literature (Sarkar and Chakrabarti 2011), where the features are considered as unique if they are not found in the designs done by the other students working on similar tasks (e.g., instead of building a square shaped base for the trebuchet as the other teams did, one team designed a triangle bridge shape base). The evaluator proceeds to the second criteria if the response to the first criteria is "Yes," or assigns a score of 0 or 2.5 if the response is "No" or "Minor." The "Minor" option is when the unique feature is marginally novel and peripheral to the design goals compared to the peers' designs (e.g., the students bounded a stack of sticks together to form the body of the tower. This is unique compared to the peers' designs, but it

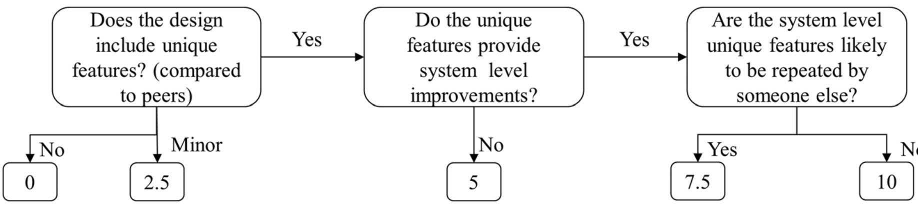


Fig. 2 Novelty rating scale in the decision tree format. The evaluation process navigated from the leftmost to the rightmost criterion. The evaluation resulted in 0 if the design had no unusual features compared to the other teams, 2.5 if the uniqueness in the design was rather minor and peripheral to the design goals, 5 if the features did not improve the system function, 7.5 if the features are integral to the system and improve the design efficiency, but did not vary greatly from the norm, and 10 if the unique features varied greatly from the normal practice and are unlikely to be repeated by someone else

does not add to the stability of the supporting structure). The second criteria asks, “Do the unique features provide system level improvements?”, where the evaluator determines if the unique features promoted the efficiency of the design (e.g., using a triangle bridge shape design in the trebuchet provides system level improvement by saving more materials than using the square base). The evaluator proceeds to the third criteria if the response to the second criteria is “Yes,” or assigns a score of 5 if the response is “No.” The third criteria asks “Are the system level unique features likely to be repeated by someone else?”. The repeatability of the unique features focused on whether the features vary greatly from the normal practice. Repeatability has been identified as a crucial indicator of novelty in design creativity research (Demirkan and Afacan 2012). The evaluator assigns a score of 10 if the system level unique features are not likely to be integrated or repeated in the designs produced by the other teams, and assigns a score of 7.5 if the system level unique features are likely to be integrated or repeated in the designs created by the other teams (e.g., placing a marshmallow inside a tower top hollow space to balance the tower, which is not likely to be repeated in the designs done by others without making fundamental changes to the design structure).

Data Analysis

Patterns of Multimodal Engineering Design Processes Across Time

In this study, we chose to analyze the multimodal design processes across time in the form of stages and the modalities, when students engage in the marshmallow tower and the trebuchet activities. These two activities were chosen for analysis because they reflect a complete design cycle from planning, building, to testing, and were each completed in a single session, which has the appropriate amount of duration that allows for in-depth and detailed second-by-second analysis. The number of videos equate to the number of design teams reported in Table 1. And the lengths of the videos are the same as the length of the design sessions as reported in the “Procedures” section.

We analyzed the students’ design behaviors using the video coding protocol in Table 2. Two graduate research assistants who had experience with engineering design conducted the coding. To avoid bias, the coders were not involved in leading the activities of the workshop sessions. To establish interrater reliability, we provided training for the coders using sample videos selected from the video recordings (Whitebread et al. 2009). When the interrater reliability reached Cohen’s $\kappa = 0.79$ (Cohen’s kappa was used because the codes are categorical), which is considered as substantial for this type of interrater reliability (McHugh 2012), the coders worked independently on different subsets of the videos for each activity. Following the behavioral coding methods used in educational research (e.g., time sampling method), the coding process involved watching the video recording of each team and pausing every 15 s to code the design behaviors exhibited by each student in the team (Deckner et al. 2006; Powell et al. 2008). Only behaviors that directly served the purpose of the design activity were coded (e.g., retrieving design materials at another table was not coded). Because the subsequent analysis of the codes was completed at the group level, we aggregated the individual student data among the team members. For example, when at least one student conducted verbal planning for more than half of the 15-s interval (Deckner et al. 2006), we aggregated that the verbal planning behavior occurred once for this team during the 15-s interval. To check the fidelity of the coding process, a third coder randomly selected 10% of the coded videos from each activity and conducted coding independently. The interrater reliability reached Cohen's kappa = 0.80, which is substantial for this type of codes (McHugh 2012).

Design Outcomes

Each design team generated one final design product for the marshmallow tower and trebuchet activities. Two researchers with experience in engineering education independently evaluated the final products' design quality and novelty using the rating scales in Figs. 1 and 2. The interrater reliability was Spearman's $\rho = 0.995$, which is sufficient for this type of scale (Best and Roberts 1975). We first calculated the average quality score and average novelty scores given by the two raters, then we generated a total design outcome score by calculating the sum of the average quality and average novelty ratings for each team.

Results

Patterns of Multimodal Design Processes Across Time

To answer the first research question, we analyzed all the teams' design processes using the protocol described in the "Methods" section.

The Design Stages The analysis showed that in both the marshmallow tower and the trebuchet activity, all teams went through the planning, building, and testing stages during the design process. To examine the teams' time distribution during design, we calculated the time each team spent on each design stage (i.e., plan, build, test) as a percentage of the total time spent on the design task (Mentzer et al. 2015). The average percentages of all teams are shown in Table 3. In the marshmallow tower activity, the teams on average spent the most time on building, followed by planning and testing. In the trebuchet activity, the most time was spent on planning, followed by building and testing.

The Design Modalities To examine how the students engaged in the design modalities, we calculated the time each team spent on each design modality during the design stages as a percentage of the total time spent on the design task. The average percentages of all teams are shown in Table 4.

In the planning stage of the marshmallow tower activity, students spent the highest percentage of time on verbal planning, followed by visual and physical planning. In the

Table 3 All teams' average time spent on each design stage as a percentage of the total time spent on the design task

Activity	Plan (%)	Build (%)	Test (%)
Marshmallow	46.50	62.50	18.87
Trebuchet	68.00	39.55	4.44

Note. The total percentage of each activity may add up to more than 100% due to the overlaps of the stages when the students in the same team engaged in different stages at the same time (i.e., two students work on planning a structure, while another student builds a part of the structure)

Table 4 All teams' average time spent on the modalities during the design stages as percentages of the total time spent on the marshmallow activity and the trebuchet activity

Activity	Verbal plan (%)	Visual plan (%)	Physical plan (%)	Verbal build (%)	Physical build (%)	Verbal test (%)	Visual test (%)	Physical test (%)
Marshmallow	32.65	25.65	22.64	36.62	55.40	8.51	14.52	7.80
Trebuchet	50.85	41.60	29.06	20.77	29.40	0.69	2.89	3.48

Note. Visual building was not observed in these activities because the tasks do not require the use of visual building such as using CAD software to build design products. Because the team members may engage in multiple modalities concurrently during the design sessions, the percentages of time spent on all three modalities in the same design stage may add up to more than 100%

building stage, a higher percentage of time was spent on the physical building than verbal building. In the testing stage, the students mainly engaged in visual testing followed by verbal and physical testing.

In the trebuchet activity, the pattern of time distribution in the planning and building stages was similar to the marshmallow tower activity: the most time was spent on verbal planning, followed by visual and physical planning; more time was spent on physical building than verbal building. In testing, the most time was spent on physical testing, followed by visual and verbal testing.

In summary, in the planning and building stages of both activities, the highest percentage of time was spent on verbal planning and physical building. In the testing stage, the highest percentage of time was spent on visual testing in the marshmallow activity and on physical testing in the trebuchet activity.

Design Outcome Scores

The design outcome score is the sum of the novelty and quality score (see Table 5), which was used to identify the high and low design outcome teams in the marshmallow and trebuchet activities for the second research questions. Based on the design outcome scores, in the marshmallow tower activity, we identified Teams 1 and 4, which were below the lower quartile (in the bottom 25%) among all teams, as the low design outcome teams; and we identified Teams 7 and 8, which were above the upper quartile among all teams (in the top 25%), as the high design outcome teams. In the trebuchet activity, we identified Teams C and D, which were below the lower quartile among all teams, as the low design outcome teams, and identified Teams E, F, and G, which were above the upper quartile, as the high design outcome teams.

The Patterns of Design Stages and Modalities in Teams with Different Design Outcomes

To answer the second research question on the patterns of the design stages and modalities in teams with different design outcomes, we conducted a case study by examining the stage and modality patterns in the design teams that received above the upper quartile and below the lower quartile design outcome scores. Using quartile as a grouping method to compare between students with different levels of performance outcomes has been used in education research in general and engineering education research in particular (Miller and Geraci 2011; Ostafichuk et al. 2014; Whitfield and Xie 2002). In addition, research on engineering design

Table 5 Team design outcome scores for the marshmallow tower and trebuchet activity

Activity		Novelty	Quality	Design outcome
Marshmallow tower				
	Team 1	1.25	0	1.25
	Team 2	5	1.25	6.25
	Team 3*	6.25	5	11.25
	Team 4	3.75	1.25	5
	Team 5*	6.25	2.5	8.75
	Team 6	2.5	6.25	8.75
	Team 7	7.5	7.5	15
	Team 8	7.5	6.25	13.75
Trebuchet				
	Team A	2.5	3.75	6.25
	Team B*	2.5	1.25	3.75
	Team C	0	2.5	2.5
	Team D	0	0	0
	Team E	6.25	10	16.25
	Team F	10	1.25	11.25
	Team G	3.75	7.5	11.25
	Team H	2.5	3.75	6.25

*Teams 3 and 5 in the marshmallow activity, and team B in the trebuchet activity were not included in the video analysis due to factors beyond our control (i.e., technical issues with the recording devices)

often uses "competitive benchmarking," a case study type method that compares one set of products or processes against more effective alternatives to shed light on areas for improvement (Bankel et al. 2005; Lamancusa et al. 1996; Marchese et al. 2003). Therefore, following this previous research on using quartiles as a grouping method for comparison and the case-based approach similar to benchmarking, we chose to conduct case by case comparisons between the high and low design outcome teams in each of the two activities (see Figs. 3 and 4). While a case study approach does not consider generalization to other populations as its purpose, it can generate in-depth knowledge regarding the specific context being studied (Yin, 2009). Moreover, even though such case-based analysis reveals no causal relationship, it can help to gain more insights into the patterns exhibited by teams with different design outcomes. To provide more context for the data, we also included the visualizations of the teams not included in the case study in the Appendix.

Using the video protocol analysis results, we visualized the low and high design outcome teams' design processes in Figs. 3 and 4. In both Figs. 3 and 4, the horizontal axis at the bottom represents the lapse of time in seconds. The diagram for each team divides into three sections representing the planning, building, and testing stages. The colored lines represent the design modalities in the different design stages. For example, the first light blue line in the low design outcome-Team 1 diagram shows all the visual planning behaviors coded at 15 s intervals. The square brackets around the colored lines highlight the initial phases of the planning stage. According to previous research that examined the crucial role of the early stages of the design processes (Cham and Yang 2005; Yang and Cham 2007), the initial planning phase is defined as the period between the beginning of the first planning behavior and the beginning of the first physical building behavior. The vertical light-gray lines that connect the colored lines highlight the instances when the verbal, visual, and physical modalities were used concurrently in the same 15-s interval in the planning stage. The

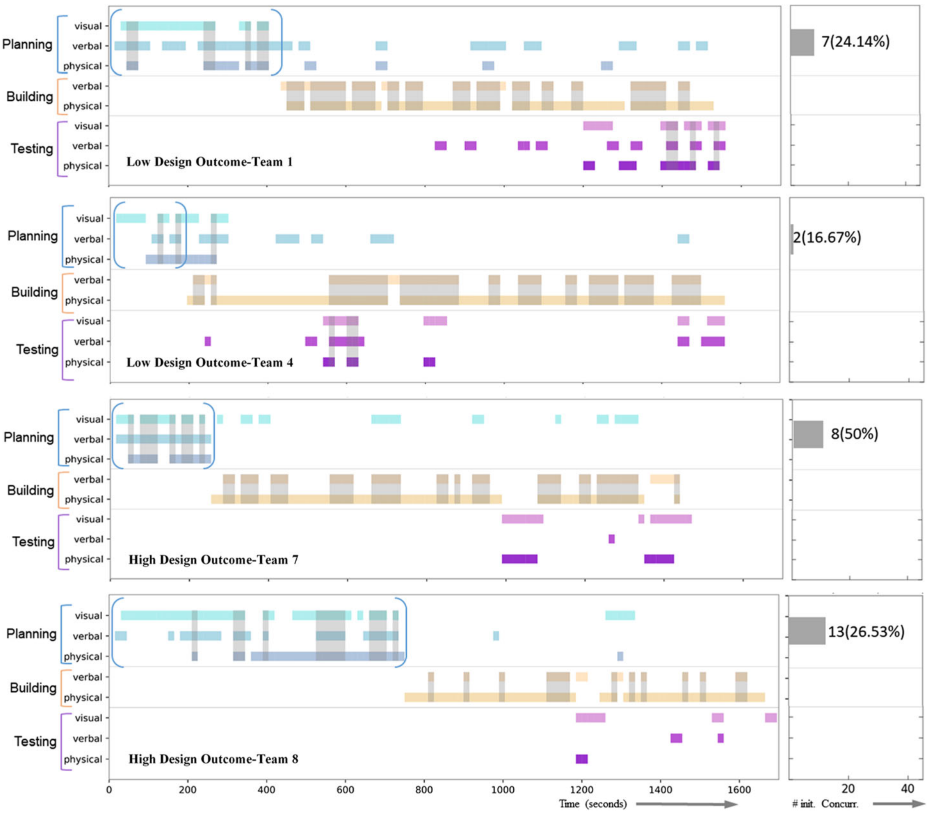


Fig. 3 Design stages and modalities of the low (Teams 1 and 4) and high (Teams 7 and 8) design outcome teams in the marshmallow tower activity. The colored lines represent the design modalities in the different design stages coded at 15 s intervals. The square brackets indicate the initial phases of the planning stage. The vertical light-gray lines highlight the concurrence of verbal, visual, and physical modalities in the initial planning stage. The horizontal gray bars on the right represent the total number of the concurrent use of the modalities in the initial phase of the planning stage

horizontal gray bars on the right represent the total number of concurrences in the planning stage.

The Switching of Stages and Modalities As shown in the visualizations in Figs. 3 and 4, all teams made switches between the design stages and modalities—a pattern similar to the iterative cycles documented in engineering design cycles in other studies (Dym et al. 2009; Safoutin 2003). Although examining the iterative revisions based on the testing results is not one of the goals of this study, the information provided in such data visualization suggests the potential of using this video analysis protocol and data visualization method to gain insights into how students conduct design in iterative cycles in hands-on settings. For example, in Fig. 3, between 0 and 900 s, the low design outcome team-Team 1 completed a cycle of planning, building, and testing before they switched to planning at around 900 s; and within this planning stage, this team either adopted all three modalities, or switched from verbal to visual, visual to verbal, verbal to physical, or physical to verbal modality. A similar pattern was also present for the high design outcome team-Team 7, where they completed a cycle of planning, building, and testing before switching to planning again at around 1100 s; and within

Fig. 4 Design stages and modalities of the low (Teams C and D) and high (Teams E, F, and G) design outcome teams in the trebuchet activity. The colored lines represent the design modalities in the different design stages coded at 15 s intervals. The square brackets indicate the initial phase of the planning stage. The vertical light-gray lines highlight the concurrence of verbal, visual, and physical modalities in the initial planning stage. The horizontal gray bars on the right represent the total number of the concurrent use of the modalities in the initial phase of the planning stage

this planning stage, this team also either adopted all three modalities or switched between the visual, verbal, and physical modalities. Overall, the teams visualized in Figs. 3 and 4 demonstrated the switching between design stages and modalities throughout the design activity. Therefore, it is valuable to explore in future studies the role of the iterative cycles of design stages and modalities in design activities. For example, real-time interviews can be conducted throughout the design process to have students reflect on how they made modifications based on the testing results in the consequent planning and building stages. With such studies, we can answer important questions regarding how students test early prototype designs and make modifications based on testing results.

Design Stages We examined the percentage of time spent on the planning, building, and testing stages by the high and low design outcome teams. As shown in Table 6, in the marshmallow tower activity, both the high and low design outcome teams spent the most time on the building stage, followed by the planning and the testing stages. However, within each design stage, there are differences: compared with the low design outcome teams, the high design outcome teams spent more percentage of time on the planning stage but less percentage of time on the building and the testing stages.

In the trebuchet activity, both the high and low design outcome teams distributed the highest percentage of time on the planning stage, followed by the building, and the testing stage. In addition, within the same design stages, compared with the low design outcome teams, the high design outcome teams spent a higher percentage of time on planning but a lower percentage of time on building and testing.

In summary, in the marshmallow tower activity, which involved relatively fewer design components and procedures, the high and low design outcome teams prioritized the building stage over the planning and testing stages. Besides, the high design outcome teams spent more time on planning, but less time on building and testing than the low design outcome team. In the trebuchet activity, which involved more design components, the high and low design outcome teams prioritized planning over building and testing. Besides, the high design outcome teams spent more time on planning, but less time on building and testing than the low design outcome teams.

The Design Modalities We also examined the percentage of time spent on the design modalities during the design stages by the high and low design outcome teams in the marshmallow and trebuchet activities. As shown in Table 7, in the marshmallow activity, the high design outcome teams spent the most time on visual planning, followed by verbal and physical planning during the planning stage. Students in the low design outcome teams resorted predominantly to verbal planning, followed by visual and physical planning. In the building stage, all the high and low design outcome teams spent more time on physical building than verbal building. In the testing stage, the high design outcome teams spent the highest percentage of time on visual testing followed by physical and verbal testing, while the low design outcome team spent the most time on verbal testing followed by visual and physical testing.

In the trebuchet activity, the high design outcome teams spent the most time on visual planning, followed by verbal and physical planning during the planning stage. The low design outcome teams spent the highest percentage of time on verbal planning, followed by physical and visual planning during the planning stage. In the building stage, all the high and low

Table 6 Percentage of time distributed to the design stages in the high and low design outcome teams in the marshmallow activity and the trebuchet activity

Activity	Team	Plan (%)	Build (%)	Test (%)
Marshmallow	High	42.60	63.94	13.77
	Low	40.78	78.60	23.30
Trebuchet	High	72.78	34.79	2.28
	Low	52.75	49.55	7.86

Note. Because the team members may engage in multiple stages concurrently during the design sessions, the percentages of time spent on all three stages in the same activity may add up to more than 100%

Table 7 Percentage of time distributed to the modalities during the design stages by the high and low design outcome team in the marshmallow activity and the trebuchet activity

Activity	Teams	Verbal plan (%)	Visual plan (%)	Physical plan (%)	Verbal build (%)	Physical build (%)	Verbal test (%)	Visual test (%)	Physical test (%)
Marshmallow tower									
	High	20.07	35.52	19.82	28.86	60.51	1.88	11.82	6.58
	Low	32.52	16.50	15.53	45.15	75.20	16.02	14.08	9.22
Trebuchet									
	High	47.15	62.24	28.49	21.62	24.82	0.24	1.13	2.27
	Low	41.30	6.18	23.77	17.60	41.85	0.00	3.25	6.51

design outcome teams spent more time on physical building than verbal building. In the testing stage, the high design outcome teams spent the most time on physical testing, followed by the verbal and visual testing. The low design outcome teams spent more time on physical testing than visual testing, with no verbal testing.

In summary, in both activities, there were more instances in the planning and testing stages where the high design outcome teams spent a higher percentage of time on the nonverbal modalities—visual and physical—than the verbal modality, whereas the low design outcome teams gave more prominence to the verbal modality than the nonverbal modalities.

The Concurrent Use of the Modalities Considering the crucial role of the early phases of the design process and the benefits of using multiple modalities during design (Dorst and Cross 2001; Yang and Cham 2007), we also examined the teams' concurrent use of the verbal, visual, and physical modalities in the initial phases of the planning stage. Based on the research on early stage design (Cham and Yang 2005; Yang and Cham 2007), the initial planning phase is defined as the period between the beginning of the first planning behavior and the beginning of the first physical building behavior. As shown in Table 8, we calculated the average percentage of the concurrent use of the visual, verbal, and physical modalities in the initial planning phase for the high and low design outcome teams (i.e., the frequency of the concurrent use of the three modalities divided by the total frequency of the occurrences when at least one modality was present during the initial planning phase).

As shown in Fig. 3 and Table 8, in the marshmallow activity, the low design outcome teams (Teams 1 and 4) on average had lower percentage of frequencies of adopting the verbal, visual, and physical modalities concurrently than the high design outcome teams (Teams 7 and 8) in the initial planning phase.

Table 8 The average percentage of the concurrent use of the visual, verbal, and physical modalities in the initial planning stage

Teams	Marshmallow tower (%)	Trebuchet (%)
High	38.27	36.13
Low	20.41	4.18

Note: The high design outcome teams: teams 7 and 8 in the marshmallow tower activity and teams E, F, and G in the trebuchet activity. The low design outcome teams: teams 1 and 4 in marshmallow tower activity and teams C and D in the trebuchet activity

As shown in Fig. 4 and Table 8, in the trebuchet activity, the low design outcome teams (Teams C and D) on average had lower percentage of instances of adopting the verbal, visual, and physical modalities concurrently than the high design outcome teams (Teams E, F, and G) in the initial planning phase.

To illustrate how students used the modalities concurrently during the early stage of design, we transcribed the following excerpt, which is part of the high design outcome team-Team 7's initial planning phase of the marshmallow tower design session. The three students in the team are labeled as a, b, and c. The transcriber of this excerpt is one of the coders who received training on the nonverbal modalities that need to be identified in the video protocol coding process. The students' speech was transcribed verbatim and the nonverbal information relevant to the video analysis protocol was identified and described in parenthesis.

> a: So triangular shape forms a strong base and it is good (using hands to gesture the shape of a triangle and sketching on paper of a triangular base).
> b and c: (both looking at the sketch) Yes.
> c: It may use a lot of spaghetti.
> b: We can cut it this way (using hands to gesture cutting in the middle of the spaghetti)
> c: (Took out a spaghetti stick from the materials bag) So what you mean is…
> b: (Took the spaghetti from C's hand and gestured breaking the stick in the middle) Break it into two pieces.
> c: No, do not break it now (stopped b from breaking the stick and took another spaghetti stick). Maybe breaking it into two makes it not strong enough.
> b: You just break it into two [parts] and make this shape (using hands to gesture and form the shape of a triangle on the table)
> c: Well…you know…
> a: Tell me what you think
> c: (Sketching on the paper of a polygonal base) I think we can do it like this (drawing one side of the base), then another one like this (drawing another side of the base), and we can have a marshmallow to stand on…
> b: But I think this will cost more spaghetti
> c: (Started counting and counted 18 in the design sketch) we have two more (students received 20 spaghetti sticks in total). (sketching on paper) We can put one here and one here.
> c: (Grabbed a marshmallow and tried attaching it on a spaghetti stick while holding the stick vertical) so we are going to put a marshmallow…
> b: No, no, it will break (a and b were watching c try out the marshmallow and spaghetti, which was about to fall)
> c: (Put the marshmallow back and visually examined the spaghetti with b)
> a: let us see how strong it is. (Using hands to bend the spaghetti stick to get a feel of how sturdy one stick is).

Note that this team utilized the verbal, visual, and physical modalities frequently and concurrently in this excerpt. Their early physical interaction with the spaghetti sticks led to an important finding later—a single stick may not be strong enough to hold a marshmallow on top. This realization may have led them to implement a support structure that resulted in a sturdy tower.

In summary, in both activities, students in the high design outcome teams had higher percentage of frequencies using the verbal, visual, and physical modalities concurrently, compared with the low design outcome teams in the initial planning phase.

Discussion

This study builds on previous research in engineering design learning by presenting a framework for examining the stages and modalities that middle school students adopted during the engineering design processes. The findings demonstrated that the students engaged in the planning, building, and testing stages, while employing one of three types of modalities, including the verbal, the visual, and the physical modality. Our findings also suggested that teams with different design outcomes exhibited patterns that vary in the adoption of modalities during the initial planning phase. Therefore, this study highlights the importance of examining the stages and the modalities of the design processes.

Patterns of the Multimodal Design Processes Across Time

The first research question explored in this study is regarding "What are the patterns of multimodal design processes across time during middle school students' engineering design activities?". In this section, we discuss findings related to the design stages and the modalities that the students employed during the design process.

Design Stages Results from this study showed that during hands-on design activities, the middle school students engaged in the design stages of planning, building, and testing. This result corroborates previous research that showed high school students conducted the problem-scoping, developing alternative solutions, and project realization stages during design think-aloud tasks (Atman et al. 2008; Mentzer et al. 2015). However, in previous research, the developing alternative solutions stage included the modeling and evaluation phases, and the project realization stage mainly involved the decision making and communication phases (Mentzer et al. 2015). In contrast, the current study included modeling as part of the building process, evaluation as part of the testing process, and decision making/communication as embedded throughout the planning, building, and testing stages. One potential rationale for this difference is that participants in previous studies generated design solutions through the think-aloud protocol and made evaluations at the conceptual level without physically testing the solutions. In comparison, participants in the current study developed solutions through physically building the designs and made evaluations based on tangible testing results, while engaging in decision making and communications throughout the planning, building, and testing processes. Although design thinking processes are inherently cognitive (Dym et al. 2005), its manifestation is always through the situated and physical dimensions that involve verbal communications with others and physical interactions with the environment. Therefore, the stages identified in the current study provided insights into students' design stages in tasks that involve physical objects and hands-on design processes.

In addition, in the marshmallow activity, students distributed the greatest amount of time to the building stage, whereas in the trebuchet activity, students spent the most time on the planning stage. This discrepancy in emphasizing different design stages may stem from the two activities' variations in design goals, requirements, and constraints. For instance, in comparison with the marshmallow tower activity, the trebuchet has a more complex design with a greater variety of coordinating parts, which takes a longer time to complete and warrants more planning effort. However, it is important to note that the students conducted the design sessions independently without receiving instructions on how much time should be spent on a certain design stage. Therefore, this result adds to the previous literature on design thinking by showing that in hands-on design activities, students tend to emphasize planning more than building for complex design tasks, suggesting that the students may recognize the necessity to focus on analyzing the problem and synthesizing solutions in such tasks (Razzouk and Shute 2012).

Design Modalities Findings from this study add to previous research by demonstrating that the middle school students adopted the verbal, visual, and physical modalities during the planning, building, and testing stages of engineering design. However, the verbal modality was not present in the previous study that used design think-aloud tasks (Mentzer et al. 2014), but was identified in the current research. Considering that the communication of design decisions and outcomes inevitably involves verbal interactions among individuals (Dym et al. 2005; Reid and Reed 2005), results from this study suggest the need to examine the use of verbal modality as a crucial component in the engineering design processes.

The visual and physical modalities identified in this study are consistent with the graphical and physical modalities identified in the previous studies that used design think-aloud tasks (Mentzer et al. 2014). However, this study differs from the previous research by suggesting that the definitions and manifestations of the modalities as well as the emphasis given to the different modalities should be examined in the context of specific design stages. For instance, regarding modality definitions and exemplifications, the graphical modality identified in the previous study mainly focused on creating sketches and visual representations (Mentzer et al. 2014), whereas the visual modality in the current study involves creating visual representations during the planning stage as well as visually observing objects during the testing stage. Similarly, while the physical modality identified in the previous study focused on creating or referencing physical objects (Mentzer et al. 2014), in the current study the physical modality refers to physically manipulating materials in the planning stage, physically building prototypes in the building stage, and physically testing prototypes in the testing stage. Regarding the emphasis given to the modalities, in the current study, the highest percentage of time was spent on the verbal modality during the planning stage and on the physical modality during the building stage in both the marshmallow and trebuchet activities. In comparison, the previous study found that students mainly emphasized graphical modeling (e.g., creating sketches) and made few references to physical modeling (e.g., creating physical objects) without differentiating the use of modalities in specific design stages (Mentzer et al. 2014). Therefore, this difference in finding highlights the necessity to examine students' use of design modalities in the context of specific design stages because the manifestation of the modalities and the emphasis given to certain modalities may vary depend on the stage in the design process.

In addition, results from this study showed that in hands-on design tasks, the visual and physical modalities are used in conjunction with the verbal modality, where the verbal interaction among people co-develops with the nonverbal interaction between people and objects (Brereton 2004; Dong 2007; Purzer 2011). As previous research has suggested, while a design idea is formed and encapsulated in verbal form on the mental plane, the solutions are also jointly portrayed and developed through the nonverbal interaction with objects on the physical plane (Howard et al. 2008; Roth 1996). Therefore, the current study builds on this research by highlighting that when the middle school students worked in hands-on environment that affords the social interaction between persons and bodily interaction with objects, there is a necessity for researchers to examine how students collectively adopt the verbal, visual, and physical modalities in the context of the different design stages.

The Patterns of Stage and Modality in Teams with Different Design Outcomes

To answer the second research question on the patterns of the design stages and modalities in design teams with different design outcomes, we examined the patterns in the design stages and modalities in the teams that received the high and low design outcome scores. It is important to note that because the analysis methods used in this study are qualitative, the findings focused on exploring the patterns in different teams rather than identifying the causal relationships between the patterns and design outcomes.

Patterns in Design Stages Results from this study suggest that students from the high and low design outcome teams may demonstrate similar patterns of time distribution by spending more time on the same design stages. For instance, the high and low design outcome teams spent more time on the building stage than the planning and testing stages in the marshmallow tower activity and more time on the planning stage than the building and testing stages in the trebuchet activity. Additionally, the high design outcome teams spent a higher percentage of time on planning, but a lower percentage of time on the building and testing stage than the low design outcome teams in both the marshmallow tower and trebuchet activities. This result adds to the previous line of work that showed time distribution in the design process differentiates engineers with various levels of experiences (Atman et al. 2007; Mentzer et al. 2015), where more experienced students spent a significantly higher percentage of time than less experienced students on information gathering, idea generation, feasibility testing, and evaluation processes.

In contrast, in previous studies, the amount of time distributed to the planning and testing related processes mainly reflect the time that the participants spent discussing the design processes in the think-aloud tasks (Mentzer et al. 2015). However, in our study, the participants engaged in hands-on design tasks that involved the interaction with the physical environment and the possibility of conducting iterative design processes. Therefore, it is possible that the high design outcome teams emphasized going back to the planning related processes such as idea generation based on the testing results and thus spent more time on planning, but less time on testing than students in the low design outcome teams. Additionally, it is also possible that the percentage of time spent on certain design stages may not be the sole indicator that differentiates high and low design outcome teams. Other factors such as using design modalities may also play important roles in the design process and influence design outcomes (Brereton 2004; de Vries 2006).

Patterns in Design Modalities Our results add to the limited research on the use of multiple modalities in design by showing that while the high design outcome teams tended to give more prominence to the nonverbal modalities (i.e., the physical and visual modalities) than the verbal modality, the low design outcome teams tended to favor the verbal modality over the nonverbal modalities during the planning and building stages. As previous research has suggested, using nonverbal modalities such as sketching or prototyping in the physical environment allows students to generate new design ideas that are not likely to be conceived through mental processes alone and can facilitate students' embodied cognition in the material context (Brereton 2004; Kirsh 2013; Roth 2001). Therefore, consistent with previous research, the high design outcome teams' emphasis on the nonverbal modalities may have contributed to the design thinking processes and by extension the design outcomes (Clark 2009; Suchman 2000).

Further, the findings from the current study also showed that the high and low design outcome teams differed in the timing of adopting the multiple modalities: the concurrent use of the verbal, visual, and physical modalities in the initial planning stage was more frequent in the high design outcome teams than the low design outcome teams. Although one type of modality may not be necessarily more advantageous than another, the act of adopting multiple modalities, such as using the verbal, visual, and physical modalities concurrently during design, may contribute to students' design effectiveness. Despite the limited research on the use of multiple modalities during design, this finding corroborates with existing research that found the imbalance in how the students adopt the different modalities may prevent the students from obtaining favorable design outcomes (Mentzer et al. 2014).

A potential rationale for the advantages of using multiple modalities during design is that the use of external representations, manifested in multiple modalities (i.e., verbal, visual, or physical), can complement and construct the design process (de Vries 2006). Previous research on embodied cognition has suggested that abstract mental operations can be off-loaded to concrete processes, such as using physical objects in prototyping or creating imagery representations for design ideas (Wilson 2002). Using multiple modalities during design in the form of concrete objects and visual representations can facilitate the design process by providing a workable medium to reduce cognitive load and promote information processing (Suchman 2000). Therefore, middle school engineering education practitioners may consider encouraging students to adopt multiple modalities concurrently during the early design phases, which can potentially promote deep level information processing for design idea generation and may benefit students' design thinking and design outcomes (Howard et al. 2008; Suchman 2000).

Limitations

This study has several limitations commonly observed in this type of qualitative studies. This study developed a video analysis protocol that examined middle school students' engineering design processes in two hands-on design activities commonly used for students in this age range. This implies that the video analysis protocol may not be generalizable to other age levels and design activities that do not involve hands-on components. In addition, the unit of analysis focused on student design teams' design processes, rather than focusing on individual students. Therefore, the results may not apply to individual design sessions. Finally, the results do not suggest causal relationships between the students' design processes and the design outcomes. Thus, cautions need to be taken when generalizing the results from this study considering the presence of these limitations.

Conclusions

This study provides theoretical contributions to the field of engineering education by proposing a framework for analyzing middle school students' design stages and modalities in the design process. The importance of understanding and applying design thinking processes has been emphasized in both research and practice, as engineering literacy is a fundamental skill for problem-solving across disciplines (Dorst 2004; Dym et al. 2005; Razzouk and Shute 2012). However, although engineering design is always situated in the material context and is multimodal in nature, previous research on design thinking processes has focused on the analysis of verbal protocols during design think-aloud types of tasks (Atman and Bursic 1996; Atman et al. 2008; Mentzer et al. 2015). There has been a dearth of research on the multimodal processes in design thinking during hands-on activities (Razzouk and Shute 2012).

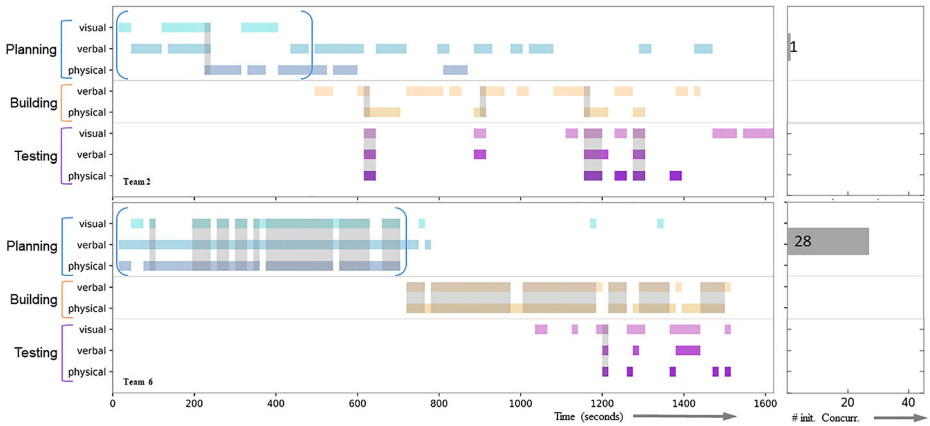
This study builds on previous literature by developing a framework to examine the multimodal processes in hands-on design tasks. We identified that the students engaged in the design stages of planning, building, and testing and adopted a combination of behaviors in verbal, visual, and physical modalities. In addition to corroborating the importance of the design cycles of planning, building, and testing, the current study also highlighted the multimodal nature of students' design processes. Thus, middle school engineering educators should not only monitor how students distribute time across the design stages, but also examine how students engage in the design modalities.

The findings also suggest that teams with different design outcomes exhibit different patterns during design, where the high design outcome teams gave more prominence to the nonverbal (i.e., physical and visual) modalities (e.g., creating design sketches and concrete prototypes) and had more concurrent use of the verbal, visual, and physical modalities during the early design phase than the low design outcome teams. Such results imply that educators can provide scaffolding for students to encourage the use of nonverbal modalities, as well as the use of multiple modalities concurrently in the early design processes.

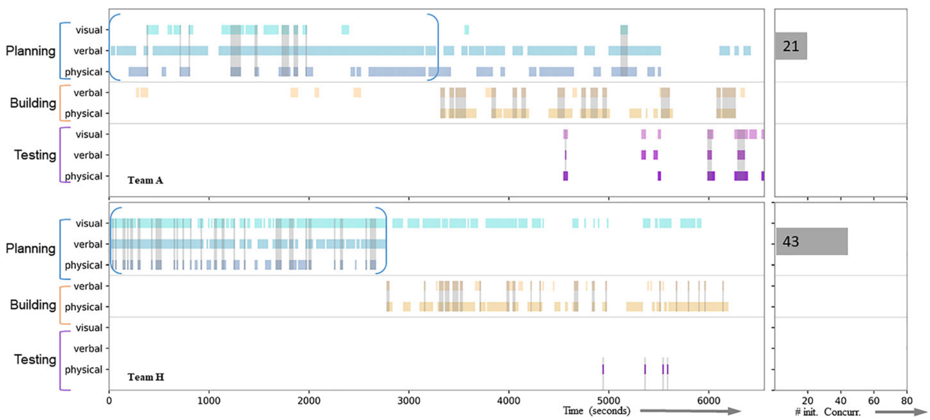
In addition, this study contributes to the methodology of engineering education research by developing design outcome measurement tools for assessing the novelty and quality of middle school students' design outcomes. This study also presented data visualization methods to identify patterns in design stages and modalities. Based on the frameworks and tools proposed in this study, future research can devise experiments to examine the influence of the design modalities on design learning and design outcomes. It is also valuable in future research to investigate the strategies for promoting the use of multiple design modalities during design activities.

Appendix. Visualizations of design processes

Teams with design outcome scores between the first and third quartile in the marshmallow tower activity:



Teams with design outcomes scores between the first and third quartile in the trebuchet activity:



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