Interdisciplinary Journal of Problem-Based Learning

Volume 12 | Issue 2 Article 4

Published online: 5-23-2018

Children's Negotiations of Visualization Skills During a Design-Based Learning Experience Using Nondigital and Digital Techniques

Shaunna Smith
Texas State University - San Marcos, shaunna.smith@hawaii.edu

Recommended Citation

Smith, S. (2018). Children's Negotiations of Visualization Skills During a Design-Based Learning Experience Using Nondigital and Digital Techniques. *Interdisciplinary Journal of Problem-Based Learning, 12*(2).

Available at: https://doi.org/10.7771/1541-5015.1747

The Interdisciplinary Journal of
Problem-based Learning

Special Issue: Tinkering in Technology-Rich Design Contexts

Children's Negotiations of Visualization Skills During a Design-Based Learning Experience Using Nondigital and Digital Techniques

Shaunna Smith (Texas State University)

Abstract

In the context of a 10-day summer camp makerspace experience that employed design-based learning (DBL) strategies, the purpose of this descriptive case study was to better understand the ways in which children use visualization skills to negotiate design as they move back and forth between the world of nondigital design techniques (i.e., drawing, 3-D drawing with hot glue, sculpture, discussion, writing) and digital technologies (i.e., 3-D scanning, 3-D modeling, 3-D printing). Participants included 20 children aged 6–12. This research was guided by Vossoughi, Hooper, and Escudé's (2016) call for explicit attention to pedagogical practices during the integration of "making" activities. Content analysis was used to analyze qualitative data, including observation, researcher/facilitator field notes, think aloud protocols, daily reflective exit tickets, and participant artifacts. Findings highlight the ways in which participants negotiated visualization skills through (a) imagining, drawing, and seeing through creating 2-D sketches, (b) reasoning and relating through writing stories, (c) transforming through 3-D extrusion, (d) observing and noticing through 3-D sculpting and 3-D scanning, and (e) manipulating through digital 3-D modeling, mental rotation, and mental transformation. Implications for formal K–12 educational contexts and teacher preparation programs are discussed.

Keywords: design-based learning, making, makerspace, pedagogy, digital fabrication technologies, 3-D printing, 3-D modeling

Introduction

"Tinkering" and "making" have become part of a popular narrative that inspires everyone to DIY (do-it-yourself) while taking creative risks and seeing the multidisciplinary connections within the designed world (Martinez & Stager, 2013; Peppler, Halverson, & Kafai, 2016a, 2016b). However, Buechley (2013) and Vossoughi, Hooper, and Escudé (2016) remind us of the tensions within the burgeoning maker movement as individuals seek to define it through disparate representations and recognitions. And though there are many potential positive contributions the maker movement has to offer education and society at large, researchers, such as Blikstein (2013), Martin (2015), and Vossoughi, Hooper, and Escudé (2016), warn us that merely giving technology to a student is not a meaningful integration effort. Teaching and learning should be examined simultaneously in order to make the most of tinkering and making within technology-rich educational contexts.

The purpose of this descriptive case study was to better understand the ways in which children use visualization skills to negotiate design as they move back and forth between the world of nondigital design techniques (i.e., drawing, 3-D drawing with hot glue, sculpture, discussion, writing) and digital technologies (i.e., 3-D scanning, 3-D modeling, 3-D printing) during a 10-day summer camp experience that employed design-based learning (DBL) strategies. This paper begins with a summary of literature on visualization skills (i.e., visual thinking and spatial skills), DBL pedagogy, and the meaningful integration of nondigital and digital techniques within maker environments. Theoretical literature is then explored to situate the researcher's lens, including Vossoughi, Hooper, and Escudé's (2016) call for explicit

http://dx.doi.org/10.7771/1541-5015.1747

attention to pedagogical practices during the integration of "making" activities. Using qualitative methods, the following research question was explored throughout the study: *In what ways do participants describe visualization skills during recurring DBL experiences involving a combination of nondigital design techniques (i.e., drawing, 3-D drawing with hot glue, sculpture, discussion, writing) and digital technologies (i.e., 3-D scanning, 3-D modeling, and 3-D printing)?*

Background

Visualization, Visual Thinking, and Spatial Skills

Visualization encompasses a variety of skills, which are relevant in many content contexts, including the arts, engineering, mathematics, science, and technology. In a broad sense, renowned perceptual psychologist Rudolf Arnheim (1969) argued for the importance of visual thinking because it is a "form of reasoning, in which perceiving and thinking are indivisibly intertwined" (p. v). This view emphasizes the important role perception plays in enhancing cognitive function. McKim (1980) expanded this notion by theorizing a visual thinking model of three types of interactive imagery, (1) seeing, (2), imagining, and (3) drawing/creating. These mental and physical negotiations are used interchangeably throughout the design process in order to produce an artifact, which is important for artistic and scientific endeavors.

Spatial skills have been categorized and defined in a more operationalized sense by many researchers; however, there is no all-encompassing definition (Maeda & Yoon, 2013; Sorby, 2009). Many researchers agree with Lohman's (1996) broad definition that spatial ability is "the ability to generate, retain, retrieve, and transform well-structured visual images" (p. 98). This definition underscores spatial skills as a cognitive function and alludes to the fact that it is a set of operationalized skills used within the more broadly defined concept of visual thinking. There are subcategories of mental processes within spatial skills, including (a) *spatial visualization*, which involves mentally moving an object using *mental rotation* of an entire object in space or *mental transformation* of only part of an object and (b) *spatial orientation*, which involves mentally moving your viewpoint while the object remains fixed in space (Sorby, 1999; Tartre, 1990).

Research shows these skills are critical for understanding geometry (Clements, 1998) and can be nurtured through training and practice (Lohman, 1996; Sorby & Baartmans, 2000), engagement in visual arts practices (Sorby, 2009; Sorby & Baartmans, 2000; Walker, Winner, Hetland, Simmons, & Goldsmith, 2011), and participation in spatially rich learning experiences (Hungwe, Sorby, Molzon, Wang, & Charlesworth, 2014; Rafaelli, Sorby, & Hungwe, 2006; Sorby 1999, 2009; Sorby & Baartmans, 2000; Sorby, Wysocki, & Baartmans, 2003). The literature also reports visualization skills can predict success in postsecondary STEM disciplines (Lohman, 1996; Maeda & Yoon, 2013; Sorby, 1999; Sorby & Baartmans, 2000; Uttal et al., 2013; Webb, Lubinski, & Benbow, 2007). Many studies report a gender gap in spatial skills where the males outperform the females, which some researchers believe to be because of innate physiological differences (Geiser, Lehmann, & Eid, 2008; Jordan, Wüstenberg, Heinze, Peters, & Jäncke, 2002; Linn & Petersen, 1985), while other researchers such as Sorby (2009) and Maeda and Yoon (2013) hypothesize are due to the inequitable exposure to spatially rich activities during younger developmental years (e.g., exposure to building blocks, interactive video games, playing sports, etc.). Sorby (2009) expresses a need for addressing these skill deficits in earlier grades by integrating spatially rich experiences into elementary and secondary contexts.

Design-Based Learning

DBL is a type of problem-based learning pedagogical approach rooted in constructionism, which asserts the belief that hands-on activities can provide personally meaningful contexts for learning because the learner builds his or her own knowledge during the process and benefits from sharing that learning with others (Papert & Harel, 1991; Peppler et al., 2016b). Blikstein (2013) extended this in the context of design experiences and the maker movement by noting these types of design-focused environments promote deep learning because "physically constructing an object is both a context for learning and an expression of learning" (p. 1). DBL can include project-based approaches to solving challenges (Hmelo, Holton, & Kolodner, 2000; Nelson, 2004) and/or creative experimentation with materials in order to to gain deeper understanding of content concepts (Petrich, Wilkinson, & Bevan, 2013; Ryan, Clapp, Ross, & Tishman, 2016). In these types of learning environments, individuals learn while engaging in the iterative design of creative artifacts, which involves development, building, evaluation, and recurring reflection (Bekker, Bakker, Douma, van der Poel, & Scheltenaar, 2015). This approach is amplified through the use of DBL instructional strategies, which encourage learners to be active participants, engage in creative problem-solving, facilitate personal connections to knowledge, experience interdisciplinary contexts, have a sense of audience, and have a space for reflection and discussion (Kafai, Peppler, & Chapman, 2009; Resnik, Rusk, & Cooke, 1999).

Maker Tools: Nondigital and Digital Tools and Techniques

Maker environments (e.g., makerspaces, labs, studios) can be good locations for DBL experiences because they can contain diverse nondigital and digital tools to allow for a variety of hands-on design techniques (Martin, 2015; Martinez & Stager, 2013; Peppler et al., 2016a). These tools can include an assortment of materials, including those for common crafts (e.g., pencils, paper, glue, pipe cleaners), recyclables (e.g., cardboard, empty toilet paper tubes, plastic bottle caps), textiles and sewing machines (e.g., fabric, felt, thread), computer-aided design software (e.g., Inkscape, Tinkercad), and digital fabrication technologies (e.g., 3-D printers, laser engraving machines, milling machines, paper/vinyl cutting machines). Researchers have reported that recurring experiences with hands-on building, constructing 3-D models in CAD software, and sketching techniques can significantly impact spatial visualization skills (Hungwe et al., 2014; Rafaelli et al., 2006; Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby, Wysocki, & Baartmans, 2003). Likewise, researchers have reported that students can learn mathematical content while engaging in these types of techniques within DBL contexts (Bush, Cox, & Cook, 2016; Bush et al., 2018).

Theoretical Framework

Vossoughi, Hooper, and Escudé (2016) present an equity-oriented framework toward a transformative vision of "making" in education, which includes a critical look at the capitalist branding of the maker movement, the general tendency to minimize the fact that diverse forms of "craft" already exist in many cultural communities, the dominant STEM focus that ignores non-STEM disciplines, "caution against the fetishization of tools" (p. 224), and key injustices of inequitable access to and/or integration of educational maker experiences. This research focuses on their theoretical suggestions for an equity-oriented approach to integrating making with explicit attention to pedagogical practices, including the crucial role educators actively play in inquiry-based learning, guided reflection, discussion of process, and battling deficit views. Because "empirical studies of learning in the context of making tend to foreground individual learning processes rather than joint activity or explicit analysis of teaching," they call for a need to analyze pedagogy in addition to individual, joint, and collaborative learning outcomes (p. 219). Similarly, Martin (2015) and Read, Iversen, Smith, Blikstein, and Katterfeldt (2015) suggest focusing less on high-tech technologies as technical tools and focusing more on how the tools support learning and the meaningful design of artifacts.

Methodology

This descriptive case study (Merriam, 1998; Yin, 2003) explored how scaffolded uses of nondigital and digital techniques influenced participants' visualization processes during a free summer camp with DBL experiences. The camp took place at a local community center in a culturally diverse mid-size city in the southwestern United States and met for two hours per day for 10 days during the month of June 2016 (total of 20 contact hours).

Participants

Participants included a convenience sample of 20 children aged 6–12, whose parents/guardians voluntarily signed them up to participate in the camp. Descriptive demographic information was not collected as part of this study due to privacy agreements with the local community center; however, it can be reported that 12 of the participants were male and 8 were female. The research team consisted of the author/researcher and three graduate assistant facilitators who were in-service teachers trained by the author/researcher prior to the summer camp.

Data

Ethnographic techniques were employed to collect qualitative data, including observation, researcher/facilitator field notes, think aloud protocols, daily reflective exit tickets, and participant artifacts. Observation involved the author/researcher being a participant observer who circulated throughout the room recording notes about participant interactions and taking photographs of participant design processes. Researcher/facilitator field notes were completed at the end of each session by the author/researcher and the facilitators as a means of reflectively recording thoughts about each session. Think aloud protocols were conducted as "a research method for understanding cognition within problem solving" because they allow participants to "express their design thinking intuitively" (Kelley, Capobianco, & Kaluf, 2015, p. 522). Each think aloud protocol was recorded in small groups of 3–4 students, which allowed the natural collaborative environment to remain intact and allowed participants to comfortably share their thoughts in action. Exit tickets were completed by the participants at the end of each of the 10 sessions, which included open-ended prompts to promote reflection about the daily activities: (a) list three things you learned today, (b) list two things you want to learn more about, and (c) list one thing you enjoyed today. Lastly, participant artifacts were photographed and used as data sources.

Data Analysis

All data were digitally transcribed for analysis in Nvivo software. Content analysis (Krippendorff, 2004) strategies were employed to analyze the data using a priori codes established from the visualization skills categories described in the literature, including *visual thinking (imagining, seeing, drawing), spatial orientation, spatial visualization, mental rotation,* and *mental transformation*. As part of the analysis process, important distinctions were made in order to distinguish between *emic* perspectives (participants' own words used to describe visualization) and *etic* perspectives (technical vocabulary used in the literature about visualization). Member check was conducted by the three graduate assistant facilitators.

Procedures

All activities took place in the community center's computer lab setting that included a flexible environment with moveable tables and chairs suitable for drawing and collaboration, as well as 10 PC computers and 10 iPad minis. The primary creative task within this DBL experience asked each participant to create his or her own "What If Creature," which could be inspired by existing animals or creatures. Based on Sorby's (2009) scaffolded activity structure that leverages eye-to-hand coordination, the activities began with two-dimensional representations that were transformed into three-dimensional representations using a variety of nondigital design strategies (i.e., drawing, 3-D drawing with hot glue, sculpture, discussion, writing) and digital techniques (i.e., 3-D scanning with MakerBot PrintShop and 123D Catch, 3-D modeling with Tinkercad, 3-D printing with MakerBot Replicator Mini). Facilitators focused on the concept of 2-D shapes and 3-D forms in order to scaffold mathematical reasoning and visualization throughout the design experience, which was inspired by literature on scaffolding activities to nurture spatial skills (Sorby, 1999; Sorby & Baartmans, 2000; Sorby, Wysocki, & Baartmans, 2003), and creative experimentation with materials in order to to gain deeper understanding of content concepts (Petrich et al., 2013; Ryan et al., 2016).

Findings

In order to demonstrate how participants negotiated visualization skills throughout the 10-day design experience, findings are arranged in the order that activities took place in order to "describe the intervention and the real-world context in which it occurred" (Yin, 2003, p. 15). Each section highlights emic perspective (i.e., participant) and juxtaposes etic perspective (i.e., relevant literature) to further explore the ways in which the participants used visualization skills to negotiate design as they moved back and forth between nondigital design and digital design techniques. The sections are as follows: (a) imagining, drawing, and seeing through creating 2-D sketches, (b) reasoning and relating through writing stories, (c) transforming through 3-D extrusion, (d) observing and noticing through 3-D sculpting and 3-D scanning, and (e) manipulating through digital 3-D modeling, mental rotation, and mental transformation.

Imagining, Drawing, and Seeing Through Creating 2-D Sketches

The first phase of the project asked the participants to sketch an original creature character using nondigital art tools (i.e., paper, pencil, crayons, colored pencils, markers). Many participants immediately dove into the task, verbalizing imaginative creatures that were unique and original. For example, Nancy began talking about all the animals she liked including, "cats, lizards, snail shells are cool, and people, of course." When asked to explain her design choices, she explained, "The snail shell is hard and protects them, the lizard arms have good claws for climbing, the lizard tail can swat away bad guys, and the people legs are strong for walking and running" (see Figure 1).

Other participants were hesitant to begin their drawing because they either did not have a clear idea that they thought was "original" or they did not feel confident about their drawing skills. "I can't draw good," exclaimed Eve as she looked disappointedly at her blank paper. The facilitators reminded Eve and the group that sketching is a process that takes practice, and they might consider starting with basic shapes to create their drawing, which they then demonstrated on the board as an example. For those still reluctant individuals, the facilitators provided a few creative prompts including, *What if you combined 3 animal characteristics into one creature? What would a sea animal look like if it lived on land? What would a polar bear look like if it lived on a tropical*

Figure 1. Nancy's creature character drawing.

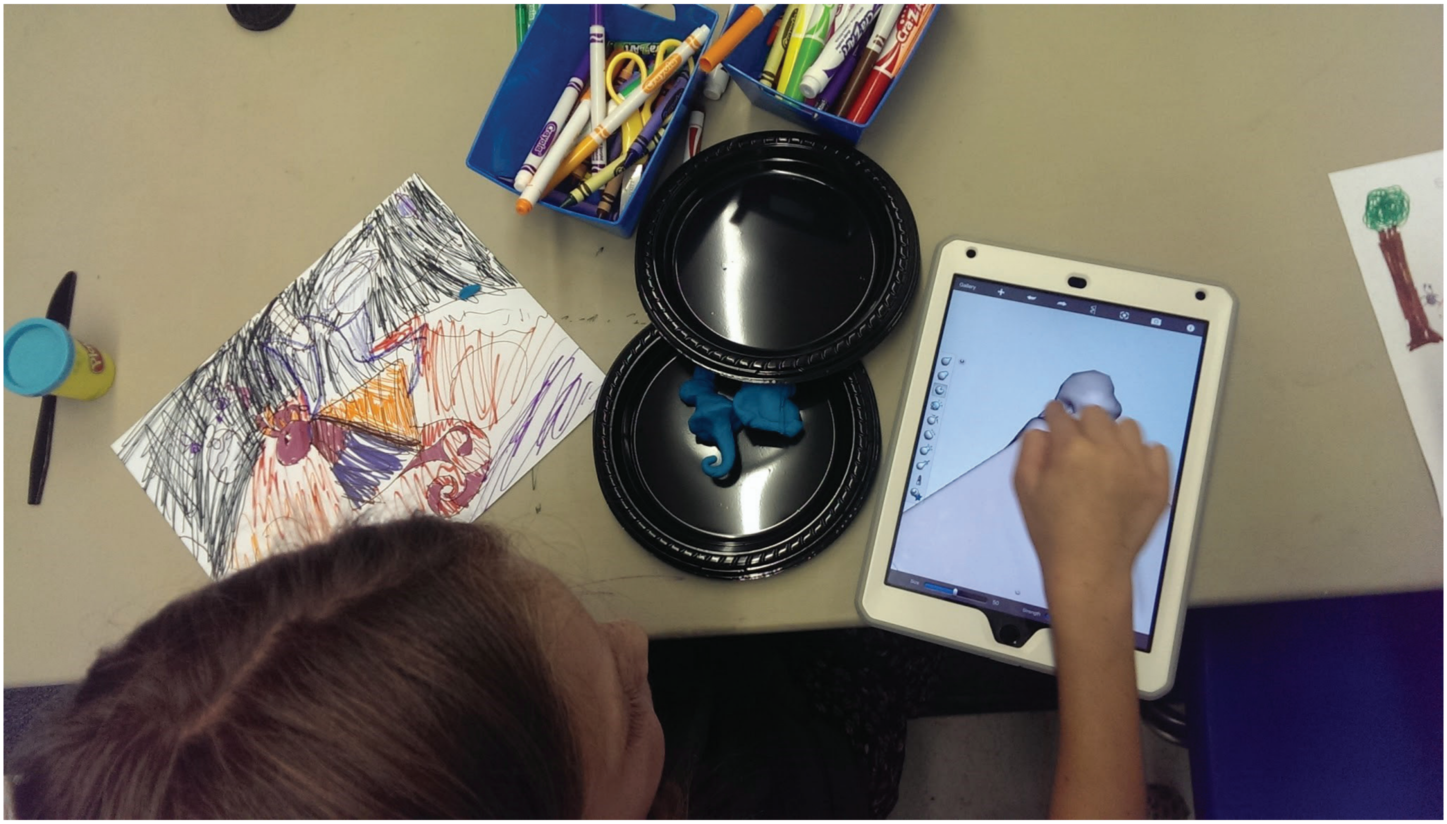

Figure 2. Eve's creature character drawing.

island? Eve began to brainstorm and excitedly said, "Ooh, or what if I added unique shapes? I could add a pyramid body, a seahorse tail, and a giraffe head. That would be pretty cool" (see Figure 2). After a few joyful giggles and encouraging smiles, Eve and the reluctant participants began sketching on their paper.

Of note in this first phase of the project, participants were demonstrating high levels of visual thinking as described by Arnheim (1969) and McKim (1980). Because they were not given pictorial prompts or resources at the beginning of the project, participants had to rely upon their ability to *imagine* imagery in order to physically create their creature *drawings*. Though this proved to be difficult at first for some, they all successfully completed the creative task by employing visual thinking strategies.

After drawings were finished, the participants were asked to describe their creature character to a partner. Facilitators reminded them to include details of character traits and also to discuss the shapes found within the character. Eve had a great beginning with her pyramid body, while other students took a little time to examine and communicate which shapes they saw in their characters. Jaime said, "My creature is unique, but I've got lots of circles that overlap to create the body." Participants began to point out shapes as if playing "Spot and Find," and many other partner pairs turned excitedly to see what others had created, turning it into a small group discussion. This additional demonstration of the *seeing* strategy for visual thinking was useful to provide participants the opportunity to verbally express what they intended the drawing to represent and to allow their partners to verbally express what they in turn saw within their peers' drawings.

Reasoning and Relating Through Writing Stories

After participants shared with their partners and small groups, the second phase of the project asked them to write a description of their creature character, which many had naturally begun to verbalize during the shared discussion in the previous phase of the project. Ysabel, who had completed her story about Mr. Gato the Evil Cat (see Figure 3, next page), encouraged her seemingly uninspired friend, Yolanda, by saying, "Write about where it lives. Who is its best friend?" To which her friend replied, "And what does it do during the day?" This friendly exchange prompted an interwoven story about how Ysabel's Mr. Gato was the evil cat who was always trying to steal food from Yolanda's Taco Dog character.

Lacy (facilitator) elaborated on this creative writing prompting by also suggesting they consider "what does the character eat" and "who is its enemy or predator?" Several

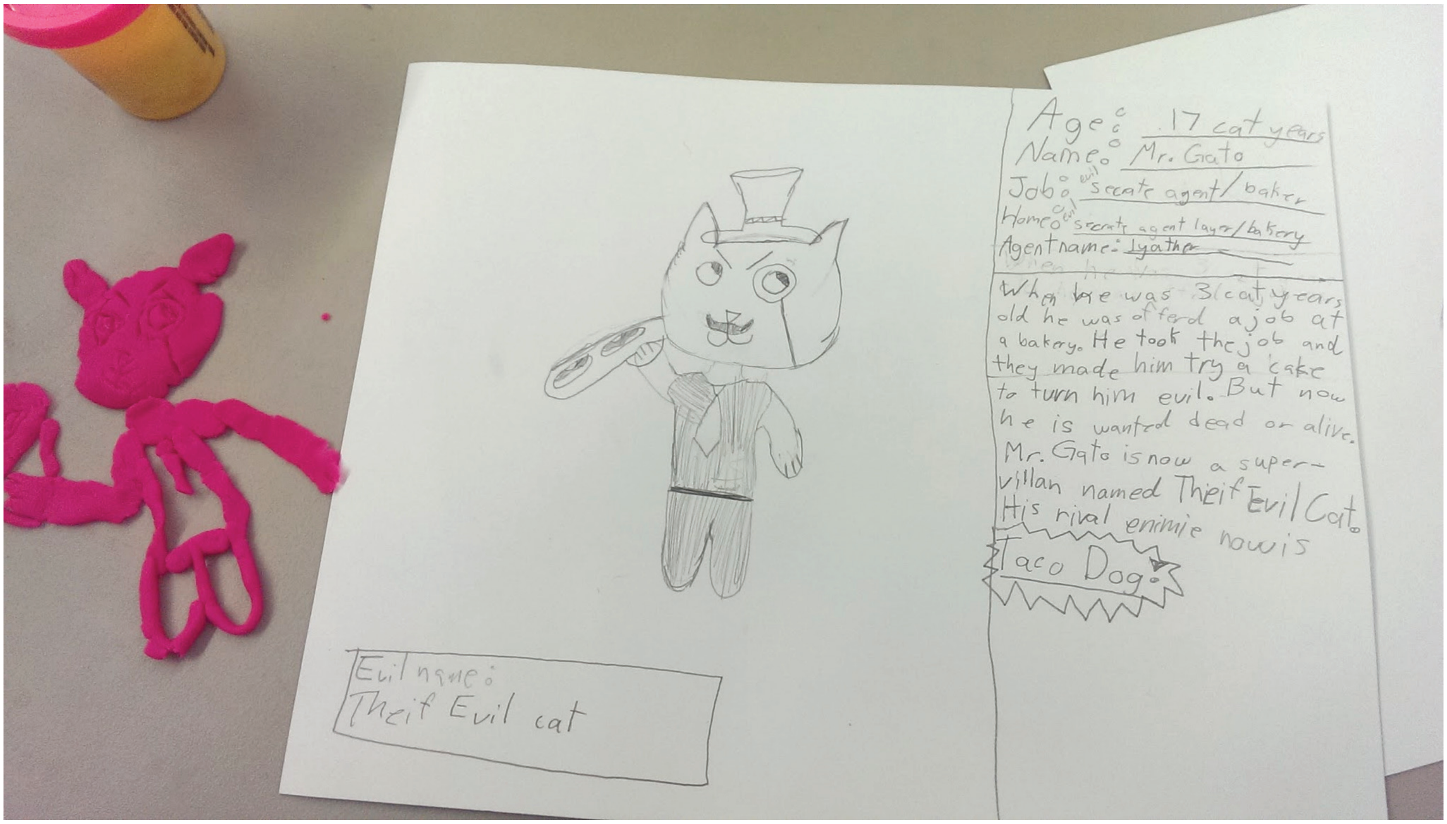

Figure 3. Ysabel's creature character drawing and writing, "Mr. Gato the Evil Cat."

participants began to verbally express their ideas out loud as they wrote, which encouraged everyone to build upon ideas. Stories of friends, hobbies, adventures, and food webs began to take shape as the participants brought their creature characters to life through storytelling.

Of note in this second phase of the project, participants extended their *imagining* skills as described by Arnheim (1969) and McKim's (1980) descriptions of visual thinking. Building upon their creature character drawings and discussions, the participants imagined elaborate backstories, environments, habitats, and storyline trajectories. This display of visual thinking extended beyond visual imagery and proved to be a useful strategy for creative writing, as is indicated in literature about the powerful cross-curricular connections between visualization and literacy (Huse, Bluemel, & Taylor, 1994; Johnson, 1991; Olson, 1992; Smith, 2012; Smith, 2013).

Transforming Through 3-D Extrusion

The third phase of the project targeted the 2-D to 3-D transformation process by asking participants to explore the concept of 3-D extrusion by using hot glue to trace their original creature character drawing. This process involved covering their drawing with parchment paper and using hot glue as a 3-D drawing medium to trace the original image. As participants worked, facilitators asked participants to confirm the shapes they were seeing. Many participants remarked they were observing that the drawing was becoming three-dimensional. Facilitators explained this was called "3-D extrusion," which meant adding layers to increase the height of the 2-D image. Michael remarked in agreement that the hot glue "adds layers so it's thicker and 3-D," which demonstrated his concept awareness of the original drawing being flat and 2-D in contrast to the 3-D extruded hot glue drawing (see Figure 4, next page).

To further enhance the transformation process, participants were asked to scan their original creature character drawings on a shared iPad using the free MakerBot PrintShop iPad app (http://www.makerbot.com/apps), which enabled them to convert their drawing into an extruded three-dimensional digital model formatted for 3-D printing. As students took turns, they discussed elements of design that contributed to the most successful scans. Natalie exclaimed, "The more difference between the dark and light parts, the better," in reference to the discovery that higher contrast drawings resulted in better scans (see Figure 5, next page).

Facilitators pointed out her observation and asked the larger group if they noticed the same thing with their scans. With prompted discovery, several students began to problem solve in a variety of ways, including some who traced

Figure 4. Michael's creature character 3-D extruded drawing using hot glue and parchment paper.

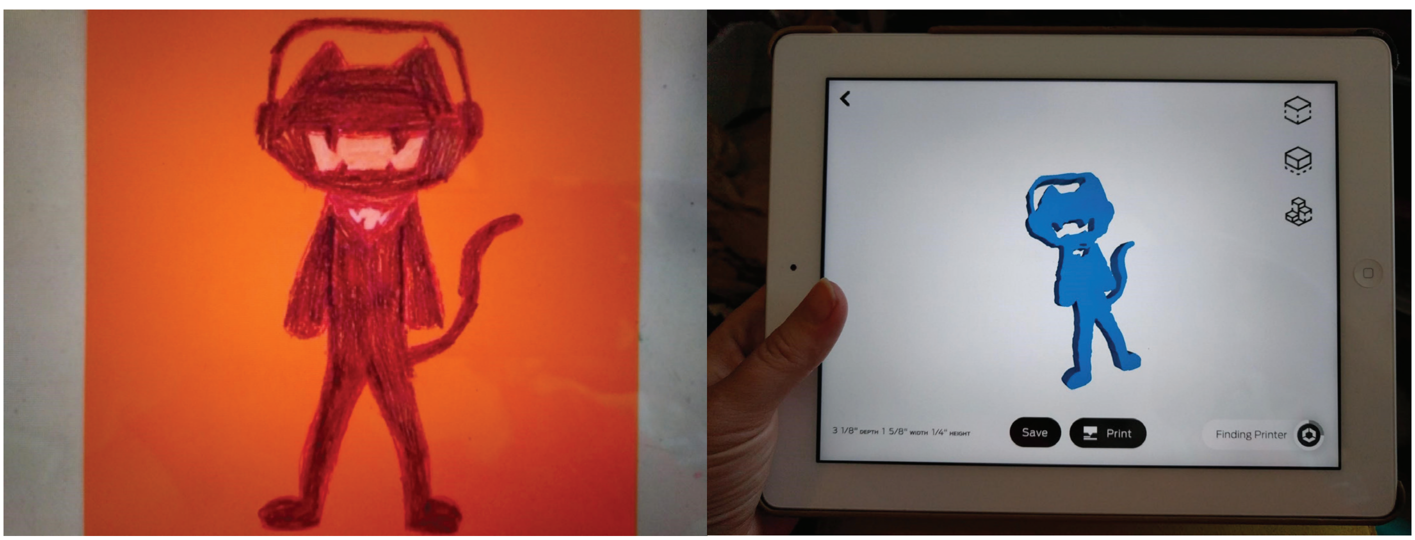

Figure 5. Natalie's creature character scan using MakerBot PrintShop app on iPad.

over their original drawings with thicker pencil or marker to create darker outlines (Abe, Richard, and Stephanie), redrew their image on white paper because the original colored paper did not provide enough contrast (Ben, Nancy, and Richard), or experimented with placement of the iPad camera or room lighting features to ensure a better photograph (Nathan and Ysabel). Each of these approaches resulted in better quality scans within the MakerBot PrintShop app and produced successful 3-D digital model files. At the end of this phase of the activity, Nancy announced a surprising realization that awareness of the 2-D to 3-D extrusion process helped her to further understand how the 3-D printing process worked because "a 3-D printer is like a hot glue gun on wheels." Facilitators responded positively that she expressed a great simile because the 3-D printer stacks layers of plastic filament to create a 3-D model object. The facilitators then

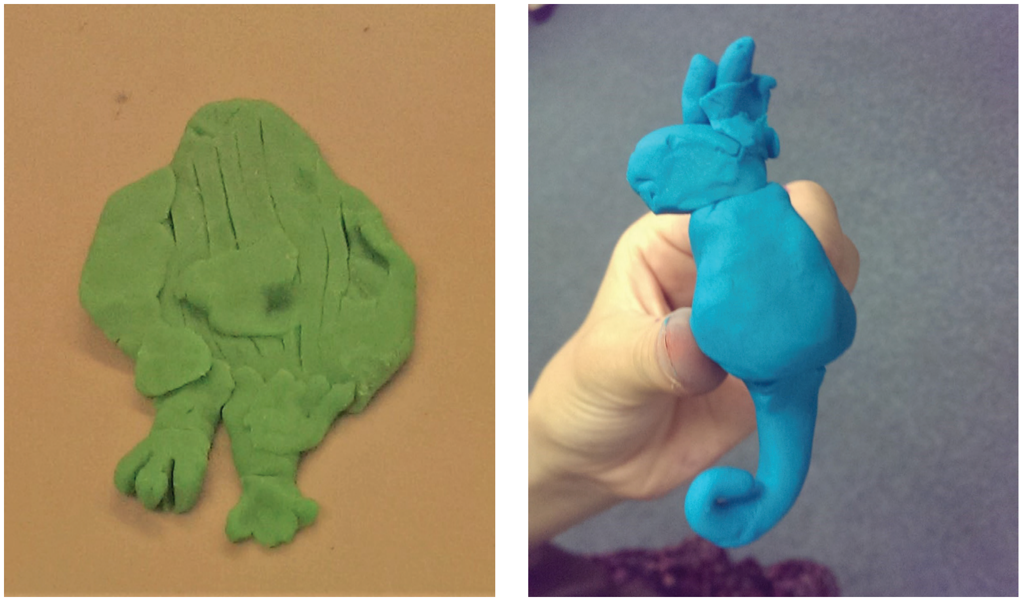

Figure 6. Zeke's creature character clay model prototypes. Left: Unsuccessful first attempt. Right: Successful second attempt.

passed around a variety of 3-D printed models and asked students to look at them and feel the visible layers of the models.

Of note in this third phase of the project, participants demonstrated several visualization skills. As described in previous phases, they demonstrated their ability to create 3-D extruded *drawings* of their creature characters, as described by McKim's (1980) visual thinking theories. This experimentation with extrusion also allowed the participants to demonstrate their *mental transformation* skills, as described by Sorby (1999) and Tartre (1990). Both with the nondigital hot glue extruded drawing and the digital design task using the MakerBot Printshop iPad app, participants were challenged to transform part of the object (i.e., extrude layers on top of layers in order to transform the flat 2-D drawing into a 3-D object).

Observing and Noticing Through 3-D Sculpting and 3-D Scanning

The fourth phase of the project asked participants to sculpt a free-standing 3-D model of their creature character using common modeling clay (i.e., Play-doh). Each participant was given a jar of clay, a paper plate, and a disposable plastic knife to produce his or her 3-D model. Facilitators explained that the previous phase of the project asked them to extrude one part of the drawing to make it 3-D; however, their task now was to make their character into a 360sculpture-in-the-round. With playful familiarity, participants molded, cut, and rolled the clay into recognizable shapes and forms. However, some participants struggled with the concept of 360sculpture-in-the-round and initially produced models that were only extruded representations of their drawings; therefore, the models were not truly 360sculpture-in-the-round. For instance, during a think aloud session Zeke said his initial model was unsuccessful because "I only used flat shapes and it couldn't stand on its own and I couldn't see the back of it"; however, he described his second attempt as successful because "I used 3-D forms to build it up all the way around" (see Figure 6).

Seeing that several participants struggled with the 360sculpture-in-the-round concept, the facilitators continued to prompt the participants to talk about how they were constructing their sculptures, encouraging them to recognize and acknowledge the intentional designs they were making. Rachel (facilitator) asked the students, "If a circle is flat and 2-D, how do we turn it into something that is 3-D? What is that called?" Nancy shouted, "It's a 3-D sphere, like a ball!" Nodding in agreement, Eve displayed her creature's body and said, "My pyramid is hard to make, but I made a box and cut some of the sides at angles to get it almost right." Alexander noted that he saw the circles in his drawing and decided it would be best if he "rolled balls and stretched them" to make his creature character 3-D, "like eggs stacked on top of each other."

In another attempt to encourage participants to recognize the shapes and forms within their creature characters, facilitators asked participants to scan their freestanding clay sculpture on the shared iPad using the free Autodesk 123D Catch iPad app (www.123dapp.com). This enabled them to engage in the process of photogrammetry by taking multiple photographs from various angles around their sculpture (approximately 20–30 photographs), which the software then digitally

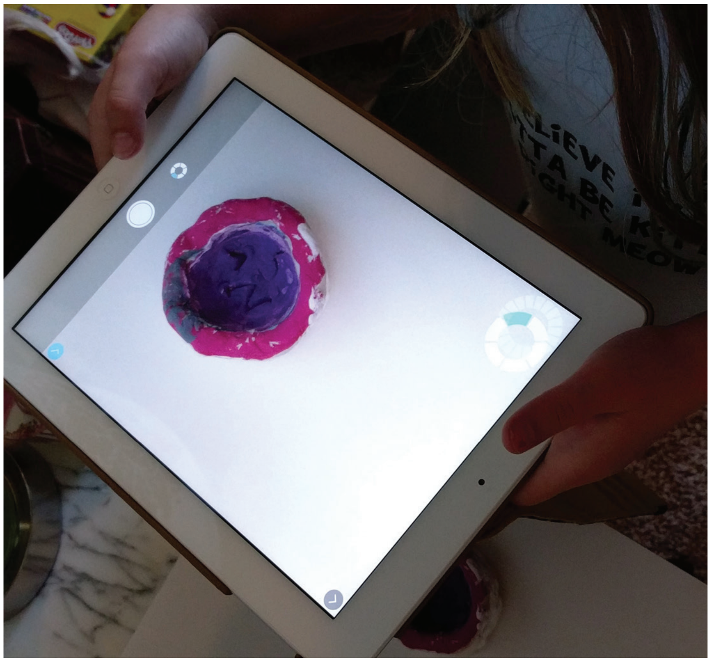

Figure 7. Miguel's creature character scan using Autodesk 123D Catch app on iPad.

stitched together to create a digital 3-D model replication of their sculpture. The process of photographing their sculpture from multiple angles forced them to take a closer look at their design. Zeke noted a "discovery of shadows and cool points of view," as he zoomed in on his digital sculpture through the iPad. Along with open discussion about the app and photography tips, facilitators encouraged participants to verbally describe their new discoveries to a partner and to talk about the specific names of the geometric 2-D shapes and 3-D forms. They were also asked to look for organic shapes and to describe them with references to familiar symbols. Miguel remarked, "I saw more shapes through the camera that I didn't notice before" (see Figure 7). When prompted by facilitators to elaborate, Miguel said he saw "holes" within his sculpture, which facilitators confirmed as "negative space."

Of note in the fourth phase of the project, participants demonstrated visual thinking in the form of *seeing*, as described by McKim (1980). Through observation of imagery they saw in the drawings and the modeling clay, participants observed shapes and forms in order to successfully create 360sculpture-in-the-round. Participants also demonstrated *spatial orientation* skills, as described by Sorby (1999) and Tartre (1990), which involved mentally moving one's viewpoint while the object remains fixed. This was demonstrated while they negotiated the challenge of 3-D scanning their sculptures using the 123D Catch iPad app, resulting in them being forced to notice small details in order to accurately capture enough overlapping photos to recreate the entire 3-D model.

Manipulating Through Digital 3-D Modeling, Mental Rotation, and Mental Transformation

The fifth phase of the project asked the participants to digitally rebuild their creature character design using free 3-D modeling software called Tinkercad (www.tinkercad.com). Paying close attention to the geometric forms needed to build the character, facilitators encouraged participants to consider how they could leverage the basic geometric forms to create the more unique organic forms needed to recreate their creature characters. Quickly participants began to verbalize that they could "overlap," "combine," and "manipulate" the forms in the software to create what they needed. Yolanda noted her creature character could be made by distorting cylinders and spheres, "if I squish and squeeze some of them" (see Figure 8, next page).

Eve remarked that she struggled to recreate her seahorse tail perfectly in the software; then she noticed the tail "looked like lots of letter c's and j's spiraling in on each other," so she manipulated those 3-D forms in the software. Others saw this creative manipulation and began using combinations of 3-D letters, punctuation symbols, and sliced or distorted geometric forms to complete irregular organic sections of their creatures as well.

In addition to manipulating the forms within the software, participants also negotiated their navigation around the 3-D modeling software. Facilitators reminded students to navigate through the 3-D world to check for alignment and specific locations of their design elements, which sparked many interesting participant reactions to the process of orienting themselves spatially. Some expressed a feeling of disorientation because they didn't immediately understand how to navigate the 360° virtual space. After numerous frustrated attempts to align his forms, Ben said, "I feel like a bird looking down at the world" as he checked to make sure his creature's eyes were in alignment with the head. "I have to keep moving around to the left and right to make sure the arms are attached," noted Jacqueline as she expressed the need to use spatial orientation skills in order to check multiple angles within the 3-D space. Completed Tinkercad models were then formatted for printing using the MakerBot Print desktop driver software that digitally resized and sliced .STL design files for the MakerBot Replicator Mini 3-D printer.

While participants were waiting for their creature characters to be printed on the 3-D printer, facilitators encouraged participants to create additional 3-D designs using Tinkercad (see Figure 9, next page). Many immediately jumped to the task, including Nichole, who said, "My Butterfly Princess lives in a castle with lots of towers made of cylinders and upside-down ice cream cones on top." Ysabel decided to design a series of "minions" to accompany her character, Mr.

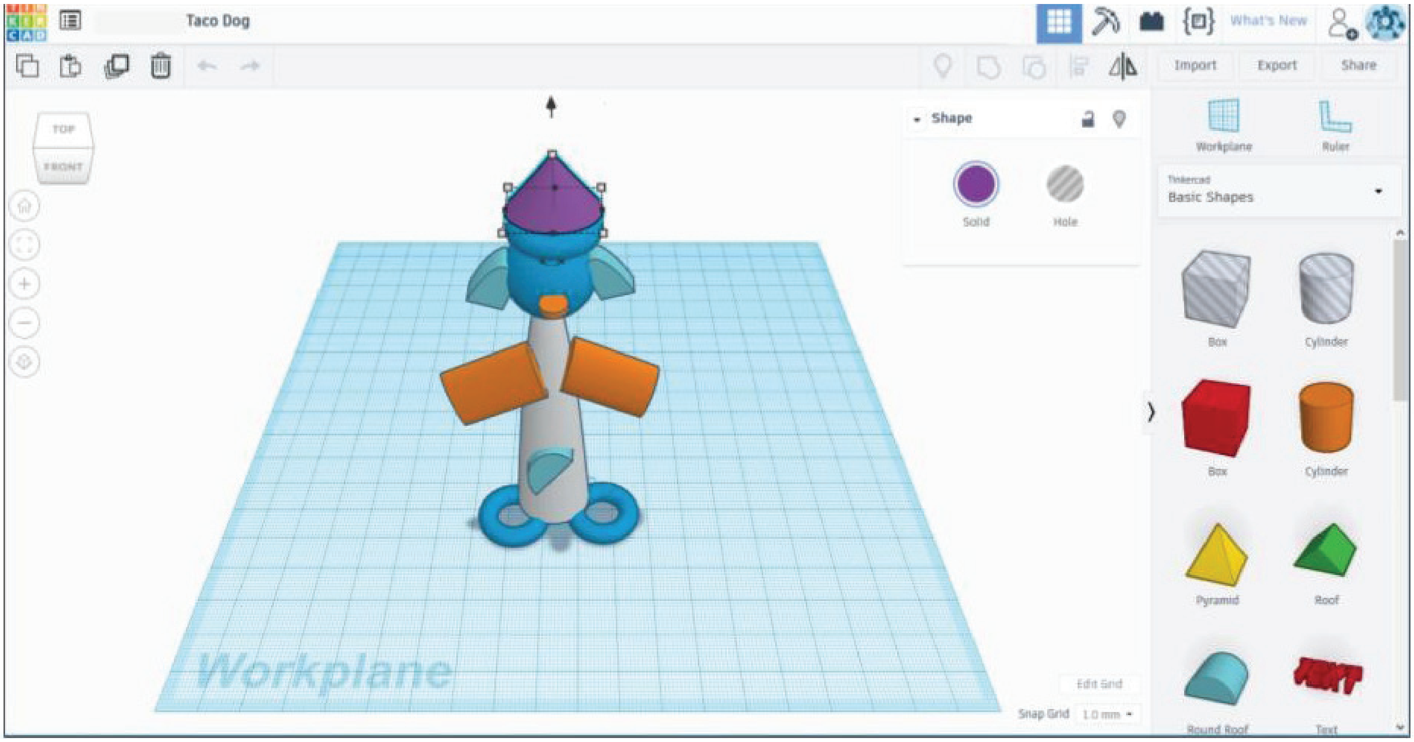

Figure 8. Yolanda's "Taco Dog" creature character digital model designed in Tinkercad.

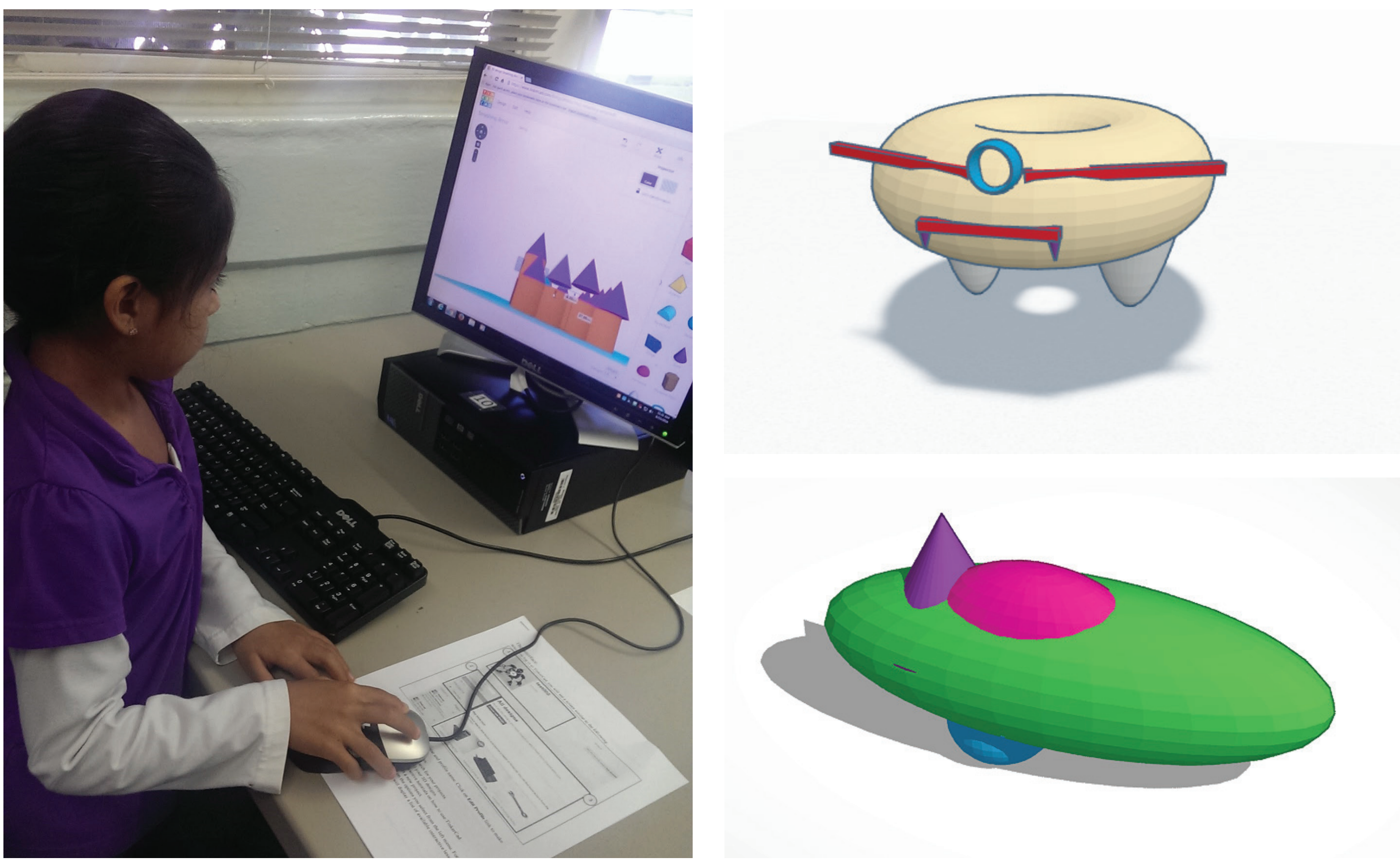

Figure 9. Left: Nichole's Butterfly Princess Castle. Top-right: Ysabel's Minion #2. Bottom-right: Michael's Watermelon Balloon Floating House.

Gato the Evil Cat. And Michael said his character "needed a watermelon balloon floating house to live in the sky."

During this closing phase of the project, participants were also asked to reflect on the entire 10-day design experience, with three participants describing it as a "transformation," making note of the "flat beginning" in two dimensions and how "it became real" in three dimensions. Participants remarked that they felt better about seeing the shapes in things around them. "I think I can see better ways to draw things now," noted Natalie. "And the blocks in the buildings, the cylinders in the bridges too," said Seth, "I see the math in the art and the art in the math."

It was here in the final phase of the project that participants demonstrated and verbalized several visualization skills interchangeably, including *mental rotation*, *mental transformation*, and *spatial orientation*, as described by Sorby (1999) and Tartre (1990). While using the CAD software to design their creature character, participants engaged in mental rotation to leverage existing geometric forms and symbols to build their structure while also manipulating portions of existing forms to transform them to fit their unique design needs. Spatial orientation was used as a mechanism to assist with the rotation and transformation of forms and also to navigate the 3-D CAD space in order to check alignment and placement of each piece.

Discussion

Connections Among Visualization Frameworks

Findings indicated how the scaffolded activities nurtured participants' spatial skills (Sorby, 1999; Sorby & Baartmans, 2000; Sorby, Wysocki, & Baartmans, 2003) and also pointed out many connections to visualization research literature. Participants' think aloud protocols revealed how the *imaging* phase of McKim's (1980) visualization model is critical during DBL activities because it involves negotiations of spatial skills (i.e., spatial visualization, mental rotation, mental transformation, spatial orientation) as described by Sorby (1999) and Tartre (1990). Figure 10 shows this connection.

Explicit Pedagogy

In line with Vossoughi, Hooper, and Escudé's (2016) call for explicit attention to pedagogical practices during the

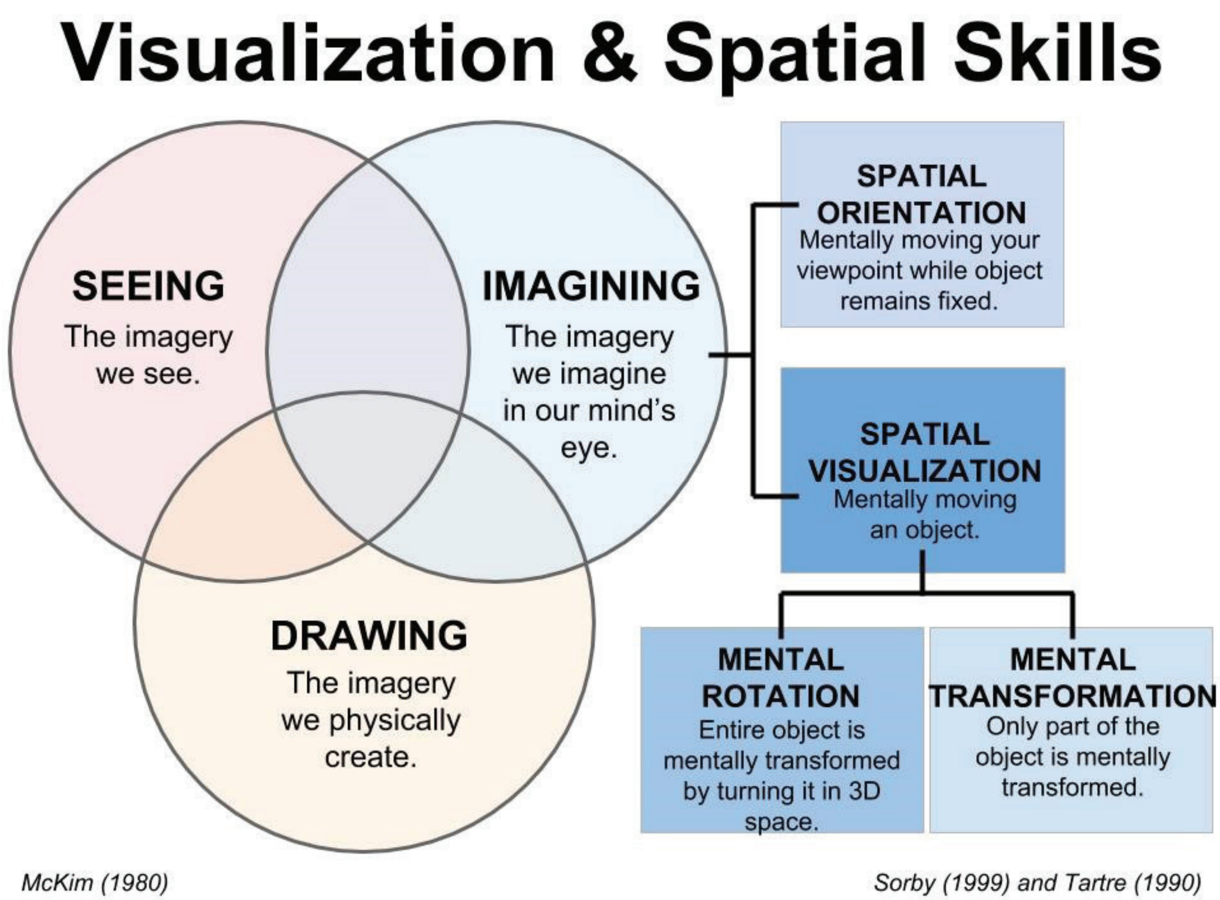

Figure 10. Connections between visualization and spatial skills.

integration of "making," the findings also highlighted active facilitator pedagogical interactions with participants throughout the DBL experience, specifically their use of thoughtful questioning to guide reflection, discuss process, and battle deficit views. During the drawing phase of the project, facilitators encouraged reluctant students with thoughtful open-ended questioning to spark ideas. Additionally, facilitators demonstrated on the board how to combine basic shapes in order to create unique drawing compositions, which students reflected on their final drawings and related back to the facilitators' earlier suggestions. During the writing phase of the project, participants demonstrated an openness and willingness to discuss new ideas and suggestions throughout the activity, which spoke to the facilitators' abilities to create and promote a safe space for students to feel comfortable to share ideas with each other. Likewise, building upon participant-generated prompts, facilitators elaborated with additional prompts to encourage creative writing and help reluctant participants feel confident to complete the task. The hot glue extrusion phase showed how facilitators celebrated Nancy's simile creation that likened 3-D printing to a hot glue gun on wheels. This encouragement generated additional enthusiasm among the students for receiving praise when they took a chance to express an observation or new way of explaining concepts. The sculpting and scanning phase displayed how facilitators' thoughtful questioning led to open discussion of newfound knowledge construction and sharing ways to describe 2-D to 3-D transformations, including observations through a camera lens. The final phase involving manipulation and 3-D modeling involved the facilitators making extra effort to encourage the participants to navigate the virtual 3-D space in various ways. This was done both to ensure the students' designs were being constructed as they intended them to be and to encourage them to design more models related to their creature character. As noted by Vossoughi, Hooper, and Escudé (2016), it is critical to highlight the facilitators' active role throughout the participants' design process in order to further help researchers understand how teaching and learning interplay within these contexts.

Implications for Teaching and Learning

The scaffolded sequence of activities and recurring contact with the participants encouraged them to think about and discuss visualization skills and concepts regularly, thus building their vocabulary and deeper understanding through the hands-on DBL experience. Participants verbally expressed the use of visualization skills to describe (a) problem-solving and intentionality within their design process and (b) mathematical concepts contributing to transformations from 2-D drawings to 3-D forms. Through visual demonstration (i.e., drawing, 3-D drawing with hot glue, sculpting, digital modeling) and verbal explanation (i.e., discussion, writing, reflection), participants were able to express design as being connected to visual arts, engineering, and mathematics throughout multiple phases of the project. Much as they did in the writing process, they acknowledged moving back and forth between visual spatial skills and the design process as they were creating, sharing, getting feedback, and revising. Participants expressed a deeper understanding of 2-D and 3-D forms, which has implications for success in educational experiences involving art, design, engineering, applied mathematics, and applied science (Lohman, 1996; Maeda & Yoon, 2013; Sorby, 1999; Sorby & Baartmans, 2000; Sorby, Wysocki, & Baartmans, 2003; Uttal et al., 2013; Webb et al., 2007).

These activities are conductive to replicability within formal learning contexts as they specifically target learning outcomes within an approachable and practical amount of time that is similar to standard classroom time constraints. Building upon Sorby's (2009) scaffolded model for teaching 2-D to 3-D transformations, this descriptive case study outlines arts-based approaches that integrate nondigital and digital design techniques. Similarly, as suggested by Bush and colleagues (2016) and Bush and colleagues (2018), this provides examples of how engaging in these types of techniques within DBL contexts can support learning mathematical content in connection with literacy and visual arts. This has implications for professional development and teacher preparation programs that seek to engage preservice and in-service teachers in authentic technology integration practices to facilitate DBL "maker" activities and inspire creative multidisciplinary learning experiences.

Limitations

This case study is limited by the observation of 20 participants over the course of 10 days within an informal learning context, which limits generalizability. However, the use of multiple data sources provides rich in-depth resources to examine visualization skills in action, which could have uses for other informal and formal learning contexts. Analysis was conducted by one participant researcher (the author), which could limit trustworthiness; however, findings juxtaposed the emic (participant) perspective and the etic (literature) perspective in order to provide further credibility within this descriptive case study. Future research could embed quantitative measures with qualitative data to explicitly examine how engagement in these types of DBL activities impacts the development of visualization skills.

Additional limitations include the fact that some of this software is either no longer available (i.e., Autodesk 123d Catch) or is no longer supported with developer updates (i.e., MakerBot PrintShop). Autodesk Recap can be used instead of Autodesk 123d Catch to engage in photogrammetry scanning of 3-D objects (https://www.autodesk.com/education/free-software/all). Instead of using MakerBot PrintShop, students can take photos of their drawings, trace them in vector software programs, save them as an .SVG file (e.g., Adobe Illustrator, Inkscape), import the .SVG into Tinkercad, and extrude a 3-D model. Though these options are not as easy as using the software originally used in this project, they still accomplish the design task.

Conclusion and Scholarly Significance of the Study

Guided by active facilitation, a DBL scaffolded experience including nondigital design techniques (i.e., drawing, 3-D drawing with hot glue, sculpture, discussion, writing) and digital technologies (i.e., 3-D scanning, 3-D modeling, 3-D printing) allowed participants to apply visualization skills and experience a deeper understanding of 2-D and 3-D forms. Findings highlight how participants negotiated visualization skills through (a) imagining, drawing, and seeing through creating 2-D sketches, (b) reasoning and relating through writing stories, (c) transforming through 3-D extrusion, (d) observing and noticing through 3-D sculpting and 3-D scanning, and (e) manipulating through digital 3-D modeling, mental rotation, and mental transformation. This paper sought to not only describe the participant learning, but also to highlight the critical impact that active facilitator participation can have on the participant experience during DBL and "maker" contexts, which Vossoughi, Hooper, and Escudé (2016) deem imperative to meaningfully integrate "making" in learning contexts.

References

Arnheim, R. (1969). *Visual thinking*. Berkeley, CA: University of California Press.

Bekker, T., Bakker, S., Douma, I., van der Poel, J., & Scheltenaar, K. (2015). Teaching children digital literacy through design-based learning with digital toolkits in schools. *International Journal of Child-Computer Interaction, 5 (Digital Fabrication in Education)*, 29–38. https://doi.org/10.1016/j.ijcci.2015.12.001

Blikstein, P. (2013). Digital fabrication and "making" in education: The democratization of invention. In J. Walter-Herrmann & C. Büching (Eds.), *FabLabs: Of Machines, Makers and Inventors.* Bielefeld: Transcript Publishers.

Buechley, L. (2013). *Thinking about making*. FabLearn Keynote, San Francisco, CA.

Bush, S. B., Cox, R., & Cook., K. L. (2016). A critical focus on the M in STEAM. *Teaching Children Mathematics, 23*(2), 110–114. https://doi.org/10.5951/teacchilmath.23.2.0110

Bush, S. B., Karp, K. S., Cox, R., Cook, K. L., Albanese, J., & Karp, M. (2018). Design thinking framework: Shaping powerful mathematics. *Mathematics Teaching in the Middle School, 23*(4), E1–E5. Retrieved from http://www.jstor.org/stable/10.5951/mathteacmiddscho.23.4.00e1

Clapp, E. P., Ross, J., Ryan, J. O., & Tishman, S. (2016). *Maker-centered learning: Empowering young people to shape their worlds*. San Francisco, CA: Jossey-Bass.

Clements, D. H. (1998). Geometric and spatial thinking in young children. *An Investigation of the Development of Elementary Children's Geometric Thinking in Computer and Non-computer Environments*. Arlington, VA: National Science Foundation, NSF MDR-8954664.

Geiser, C., Lehmann, W., & Eid, M. (2008). A note on sex differences in mental rotation in different age groups. *Intelligence, 36*, 556–563. https://doi.org/10.1016/j.intell.2007.12.003.

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *Journal of the Learning Sciences, 9*(3), 247–298.

Hungwe, K., Sorby, S., Molzon, R., Wang, M., & Charlesworth, P. (2014). Supporting the development of spatial visualization in middle grade and high school students. *Journal of Women and Minorities in Science and Engineering, 20*(4), 379–393.

Huse, V. E., Bluemel, L., & Taylor, R. H. (1994). Making connections: From paper to pop-up books. *Teaching Children Mathematics*, *1*(1), 14–17.

Johnson, P. (1991). *Pop-up paper engineering: Cross-curricular activities in design technology, English, and art*. London and Philadelphia, PA: Falmer Press.

Jordan, K., Wüstenberg, T., Heinze, H.-J., Peters, M., & Jäncke, L. (2002). Women and men exhibit different cortical activation patterns during mental rotation tasks. *Neuropsychologia, 40*, 2397–2408. https://doi.org/10.1016/S0028-3932(02), 00076-3.

Kafai, Y. B., Peppler, K., & Chapman, R. (Eds.) (2009). *The computer clubhouse: Creativity and constructionism in youth communities.* New York, NY: Teachers College Press.

Kelley, T. R., Capobianco, B. M., & Kaluf, K. J. (2015). Concurrent think-aloud protocols to assess elementary design students. *International Journal of Technology and Design Education, 25*(4), 521–540. https://doi.org/10.1007/s10798-014-9291-y

Krippendorff, K. (2004). *Content analysis: An introduction to its methodology* (2nd ed.). Thousand Oaks, CA: Sage.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*, 1479–1498. https://doi.org/10.2307/1130467.

Lohman, D. F. (1996). Spatial ability and g. In I. Dennis & P. Tapsfield (Eds.), *Human abilities: Their nature and measurement* (pp. 97–116). Hillsdale, NJ: Lawrence Erlbaum Associates.

Maeda, Y., & Yoon, S. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R). *Educational Psychology Review, 25*(1), 69–94.

Martin, L. (2015). The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research, 5*(1), 30–39. https://doi.org/10.7771/2157-9288.1099.

Martinez, S. L., & Stager, G. S. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Torrance, CA: Constructing Modern Knowledge Press.

McKim, R. H. (1980). *Experiences in visual thinking*. Boston, MA: PWS Publishers.

Merriam, S. (1998). *Qualitative research and case study applications in education*. San Francisco, CA: Jossey-Bass.

Nelson, D. (2004). Design based learning delivers required standards in all subjects K–12. *Journal of Interdisciplinary Studies, 17*(3), 1–9.

Olson, J. (1992). *Envisioning writing: Toward the integration of drawing and writing*. Portsmouth, NH: Heinemann.

Papert, S., & Harel, I. (1991). *Constructionism: Research reports and essays*. Norwood, NJ: Ablex.

Peppler, K. A., Halverson, E., & Kafai, Y. B. (2016a). *Makeology, Volume 1: Makerspaces as learning environments.* New York: Routledge.

Peppler, K. A., Halverson, E., & Kafai, Y. B. (2016b). *Makeology, Volume 2: Makers as learners.* New York: Routledge.

Petrich, M., Wilkinson, K., & Bevan, B. (2013). It looks like fun, but are they learning? In M. Honey & D. Kanter (Eds.), *Design, make, play* (pp. 50–70). New York and London: Taylor and Francis. https://doi.org/10.4324/9780203108352

Rafaelli, L., Sorby, S. A., & Hungwe, K. (2006). Developing 3D spatial skills for K–12 students. *Engineering Design Graphics Journal, 70*(3), 1–11.

Read, J., Iversen, O., Smith, R., Blikstein, P., & Katterfeldt, E. (2015). Digital fabrication in education: Expanding the research towards design and reflective practices. *International Journal of Child-Computer Interaction*, *5*1(2). https://doi.org/10.1016/j.ijcci.2016.01.001

Resnick, M., Rusk, N., & Cooke, S. (1999). The computer clubhouse: Technological fluency in the inner city. In D. A. Schon, B. Sanyal, & W. J. Mitchell (Eds.), *High technology and low-income communities: Prospects for the positive use of advanced information technology* (pp. 263–285). Cambridge and London: MIT Press.

Ryan, J. O., Clapp, E. P., Ross, J., & Tishman, S. (2016). Making, thinking, and understanding: A dispositional approach to maker-centered learning. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology, Volume 2: Makers as learners* (pp. 29–44). New York and London: Routledge.

Smith, S. (2012). Where art & technology unite: Exploring pop-up books and digital fabrication in the digital paper engineering club. *Learning & Leading with Technology, 39*(8), 26–28.

Smith, S. (2013). Through the teacher's eyes: Unpacking the TPACK of digital fabrication integration in middle school language arts. *Journal of Research on Technology in Education, 46*(2), 207–227.

Sorby, S. (1999). Developing 3-D spatial visualization skills. *Engineering Design Graphics Journal, 63*(2), 21–32.

Sorby, S. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, *31*(3), 459–480.

Sorby, S., & Baartmans, B. (2000). The development and assessment of a course for enhancing the 3-d spatial visualization skills of first year engineering students. *Journal of Engineering Education, 89*(3), 301–307. https://doi.org/10.1002/j.2168-9830.2000.tb00529.x

Sorby, S., Wysocki, A. F., & Baartmans, B. J. (2003). *Introduction to 3D spatial visualization: An active approach*. Clifton Park, NY: Delmar Cengage Learning.

Tartre, L. (1990). Spatial orientation skill and mathematical problem solving. *Journal for Research in Mathematics Education, 21*(3), 216–229. https://doi.org/10.2307/749375

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, (2), 352.

Vossoughi, S., Hooper, P. K., & Escudé, M. (2016). Making through the lens of culture and power: Toward transformative visions for educational equity. *Harvard Educational Review, 86*(2), 206–232. https://doi.org/10.17763/00178055.86.2.206.

Walker, C., Winner, E., Hetland, L., Simmons, S., & Goldsmith, L. (2011). Visual thinking: Art students have an advantage in geometric reasoning. *Creative Education*, *2*(1), 22–25.

Webb, R. M., Lubinski, D., & Benbow, C. P. (2007). Spatial ability: A neglected dimension in talent searches for intellectually precocious youth. *Journal of Educational Psychology*, *99*, 397–420.

Yin, R. K. (2003). *Case study research: Design and methods* (3rd ed.). Thousand Oaks, CA: Sage.

Dr. Smith is an Assistant Professor of Educational Technology in the Department of Curriculum and Instruction at Texas State University. Her research interests focus on technology integration strategies within K–12 and postsecondary learning environments. As a former secondary art and technology teacher, she is particularly interested in exploring

how the hands-on use of design-based technologies (e.g., "making" and "makerspaces," digital fabrication, 3-D modeling and printing, computer programming, and robotics) can impact multidisciplinary learning that transcends traditional content contexts. Through her mobile makerspace initiative, The MAKE Lab (http://themakelab.wp.txstate.edu), she is currently researching how recurring experiences with these design-based technologies impact visual spatial skills, self-efficacy, and positive attitudes toward failure (e.g., persistence in the face of obstacles; reconceptualization of failure as a paradigm for creative learning) with teachers and K–12 students. These concepts are also part of her research as Co-Director of Bobcat Made, which is the collaborative university makerspace.