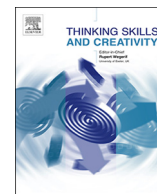




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Debugging open-ended designs: High school students' perceptions of failure and success in an electronic textiles design activity

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ARTICLE INFO

Keywords:

Electronic textiles
Debugging
Open-ended design
Productive failure
Learning designs

ABSTRACT

Research on productive failure has examined the dimensions which are most beneficial for students' learning of well-defined canonical problems in math and science. But failure plays an equally important role in solving open-ended, or ill-defined, design problems that have become prominent in many STEM-oriented maker activities. In understanding the role of failure in open-ended design tasks, we draw on Kapur's conceptualization of productive failure and connect it to research on the role of construction in learning. We report on findings from an eight-week long workshop with 16 high school freshmen (13–15 years) who engaged in an open-ended design task with electronic textile materials. In electronic textile design tasks, a small computer, sensors, and actuators are stitched together with conductive thread to create a circuit. Our analysis focused on students' debriefing interviews addressing two questions: (1) What range of debugging challenges do youth report encountering when creating e-textiles? and (2) How do youth draw upon the available tools and materials to generate and implement solutions to these challenges? In the discussion, we address how our findings from examining open-ended e-textiles design challenges, students' perceptions on failure, and their resolutions contribute to the growing work on productive failure as a learning design with applicability to open-ended design tasks.

1. Introduction

One of the current debates in the learning and educational sciences is the role of instructional supports in learning and problem solving (Kapur, 2016). While one group argues for the “productive success” model by providing direct instruction and scaffolding (Kirschner, Sweller, & Clark, 2006), others point to “productive failure” with delayed instruction as an equally promising direction for supporting student learning (Kapur, 2008; Kapur & Bielaczyc, 2012). Much like the proponents of productive success who see scaffolds and collaborations as essential in propelling students' learning forward, the supporters of productive failure focus on better understanding the role of multiple representations and solutions, their role in activating prior knowledge, and the nature of peer support during the solution generation phase to identify which dimensions are most productive for which students and under which conditions (Kapur & Rummel, 2012). Most of these studies, however, have focused on getting students to solve well-defined canonical problems in STEM contexts such as mathematics and science (Kapur, 2008; Kapur & Bielaczyc, 2012).

Failure plays an equally important role in solving open-ended, or ill-defined, design problems that have become prominent in many STEM-oriented maker activities (Honey & Kanter, 2013; Peppler, Halverson, & Kafai, 2016a, 2016b). The Maker movement refers to the growing number of individuals involved in making things for useful and playful purposes, often integrating the physical

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<https://doi.org/10.1016/j.tsc.2018.03.004>

Received 6 July 2017; Received in revised form 5 March 2018; Accepted 14 March 2018

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and the digital and sharing their creations through online forums and maker faires (Halverson & Sheridan, 2014; Martin, 2015). While the Maker Movement began largely with adult hobbyists, it quickly moved into formal and informal educational spaces in the United States and is closely connected to the need for qualified individuals to fill STEM jobs. Maker activities are particularly promising alternatives to traditional STEM pathways, because they not only engage youth with authentic disciplinary knowledge by generating creative solutions to important problems, but also connect with a culture of entrepreneurship and manufacturing by bringing solutions to market (e.g., Pepler et al., 2016a, 2016b). Because students in these contexts are creating something from scratch and there is no one right solution, they encounter many problems in the design and construction phases of their projects (Calabrese Barton, Tan, & Greenberg, 2017; Kafai, Lee et al., 2014). This process of encountering and resolving problems is known as debugging in coding or trouble-shooting in engineering.

In this paper, we examine debugging in the context of an open-ended design task that engaged high school students in designing electronic textiles (hereafter: e-textiles) involving computing and engineering. E-textiles include microcontrollers, sensors for sound, touch and light, and actuators such as LEDs and buzzers that can be sewn into textiles to make interactive wearables (Buechley, Pepler, Eisenberg, & Kafai, 2013). In addition to these electronic components, students also have a variety of tools at their disposal, including paper and markers for sketching circuits, scissors for cutting craft materials, and several kinds of tape useful for triaging short circuits caused by loose or overlapping threads. Making an e-textile incorporates multiple opportunities for students to experience and engage with failure: it involves learning not only about crafting, designing functional circuits, and writing code that controls the circuits (Kafai, Lee et al., 2014) but also identifying and fixing bugs in each of these, at times intersecting, domains. To understand better the nature of failure in open-ended design tasks and how solution generation is facilitated by the available tools and materials, we examined not only the final artifacts generated by 16 high school freshmen (13–15 years-old), but also interviewed students about their debugging experiences asking them specifically about moments of failure and solution generation in their design processes. Our analyses were directed by two questions: (1) What range of challenges do youth report encountering when crafting e-textiles? and (2) How do youth draw upon the available tools and materials to generate and implement solutions to these challenges? In the discussion we return to Kapur's notion of productive failure and address how our findings from examining students' e-textiles design challenges and debugging processes might contribute to the growing body of work on failure as productive in open-ended design tasks where there are multiple possible solutions and where tools can play a role in facilitating solution generation and activating prior knowledge (Bruner, 1973).

2. Productive failure and open-ended educational design projects

In understanding the role of failure in open-ended design tasks, we draw on Kapur's conceptualization of productive failure and connect it to research on both the role of construction in learning and students learning to problem solve in other contexts, such as computing and engineering. The productive failure framework is a learning design that consists of four central mechanisms embedded in two phases (Kapur, 2015; Kapur & Bielaczyc, 2012). In the first phase learners work collaboratively to generate and explore multiple representations and solution methods (RSMs) to a challenging, ill-structured problem. While generating solutions and representations activates learners' prior knowledge, the problem should be too challenging for the learners to solve without assistance, meaning that failure is encountered. Thus, in the second phase the RSMS generated by the learners are compared and contrasted with canonical RSMS and learners consolidate knowledge, integrating the solutions they generated with the targeted concepts. Ultimately, learners who initially experienced failure when faced with an ill-structured problem are better equipped to solve a well-structured problem as well as subsequent ill-structured problems (Kapur, 2008). Further, the more solutions generated in the first generation and exploration phase, the more knowledge gained, what Kapur (2015) has called the solution generation effect.

In contrast, in open-ended projects, learners also encounter challenges but the two phases are more fluid and supported by physical tools and materials. There is an initial conceptualization phase, constrained by features of the design task environment, but design tasks, by definition, tend to have ill-defined solutions with many component parts that are interconnected (Goel & Pirolli, 1992). In other words, open-ended design projects are not targeting one concept at a time, but often many interrelated ones. Challenges that need debugging or troubleshooting can be many, and problems can also be of an interdependent nature (e.g., circuit design impacts coding etc.). Learners must be able to isolate which problem to tackle first—something that in typical productive failure situations is clearly separated in two phases, as the learner is guided through a canonical solution in the consolidation phase. Further, in open-ended design tasks, there are often multiple correct solutions, making the consolidation phase less obvious. Without a clear canonical solution in open-ended tasks, learners may receive comparably significant feedback from the tools and materials with which they engage.

In a productive failure learning design, much of the task design is pre-conceptualized to engage learners in the most productive way in the problem space. In more open-ended activities, similar constraints can be applied through managing the difficulty of the design task to challenge learners but not be impossible. For example, building on prior work (Griffin, Kaplan, & Burke, 2012), Fields, Searle, and Kafai (2016) proposed “deconstruction kits” as a scaffold to assist students in solving open-ended design challenges. They designed completed e-textiles projects that were embedded with common student errors, such as mixing up the polarity of a light in the circuit or incorrectly coding for the circuitry that was built. Importantly, these errors highlighted the interconnectivity of parts (Goel & Pirolli, 1992), or the places where craft and circuitry or circuitry and code intersected, creating new and unanticipated challenges for learners. Students worked in pairs to solve the errors embedded in the deconstruction kits *after* beginning work on individual e-textiles projects, suggesting that work on individual projects, supported by tools and materials, can assist with activating students' prior knowledge. Whereas productive failure tasks rely on the problem structure to provide feedback to the learner, e-textiles design tasks depend on the construction tools and materials to provide feedback to the learner in the initial phases.

To contextualize this design process, we draw on Bruner's (1973) understanding of the role of construction in learning. Examining a small number of eight year-olds learning about quadratic constructions using manipulables, Bruner observed that the construction process provided a basis for developing mental imagery, particularly as learners moved through phases of "construction, un-construction, and reconstruction" (Bruner, 1973, p. 429). Further, learners could move through construction processes even as their knowledge of the targeted abstract concept was still in development. In our case, students can move through phases of constructing and deconstructing e-textiles even in the absence of a working knowledge of craft, circuitry, and computing and the ways in which these domains overlap within e-textiles. Moreover, Papert (1980) presents a similar perspective for construction in the learning process; for example, his construct of "objects-to-think-with" (p. 11) argues for the significance of providing learners with artifacts with which they can physically manipulate abstract concepts. Here, we bring together these perspectives on the role of construction in learning with Kapur's (2008) notion of productive failure. We hypothesize that students' abilities to generate solutions are facilitated by the tools and materials available to assist in the activation of prior knowledge.

In open-ended maker activities, which often involve the integration of computing and engineering, failure plays a constant and prominent role in students' overall learning. The process of debugging in open-ended design activities mirrors the process of generating multiple solutions in productive failure activities, however, debugging is an inherent part of the entire design process rather than being a beginning or early phase (Kafai & Burke, 2014, 2016; Soloway & Spohrer, 1989). Research on debugging reaches back into the early days of educational computing. As Papert (1980) noted, "when you learn to program a computer you almost never get it right the first time" (p. 23). Studies on debugging have revealed that learners not only encounter various bug types in their programs but also have significant problems with identifying bugs, let alone fixing them (McCauley et al., 2008). These debugging problems are not just simple syntax issues such as forgetting commas or making typos but also are semantic in nature, dealing with errors in logic design. Additionally, debugging is not just an issue in computer science but also in engineering education, especially when considered alongside other important skills such as decision-making, emotional intelligence, and perseverance (e.g., Patil & Codner, 2007). E-textiles bring engineering and computer science together, especially in the area of debugging designs.

Open-ended design projects, where students need to identify, debug, and solve problems in multiple, overlapping domains, provide a rich context for experiencing and addressing failure (Litts & Ramirez, 2014). For instance, in the context of robotic design, students not only have to build motor-driven models with active sensors but also have to code and debug the programs that operate motors and sensors independently in the field, without any human direction (Sullivan, 2008). Similarly, in e-textiles projects, students must navigate the overlapping domains of crafting, circuitry, and coding. In previous research studies of e-textiles, we examined how these overlapping domains, where materials behave in unexpected ways, are rich spaces for student learning (Kafai, Lee et al., 2014). During the creation of an e-textile project, problems can occur in the code, in the circuitry, and in the physical design itself, and students need to test and isolate problems, often fixing multiple co-occurring issues that add to the complexity and challenge of the project (Kafai, Fields, & Searle, 2014). We observed how students' experiences with failure occurred not only within each domain, but also at the intersections of domains (i.e., crafting, coding, and circuitry) (Kafai, Fields et al., 2014). Students have to learn and coordinate multiple representations, for example, blueprints for circuit design and program code for the microcontroller. Thus, debugging an e-textile project involves multiple skills including the ability to observe what's happening, visualize what should be happening instead, and create abstractions and patterns that facilitate ease of coding (Yadav & Cooper, 2017). Importantly, e-textiles and other open-ended STEM maker activities are typically materially and computationally rich contexts, providing additional resources and feedback mechanisms for solution generation and problem solving.

In this paper, we seek to understand where failure is encountered in open-ended e-textiles design tasks and how moments of failure are supported by the available tools and materials in service of solution generation. Likewise, in projects that involve students building designs such as car ramps (Kolodner et al., 2003) or bridges (Roth, 1998), students learn not only about the qualities of materials but also about structural properties of different bridge designs. They work in teams or individually to overcome challenges by iteratively cycling through generating and implementing solutions to achieve product completion. Indeed, students' ability to debug or fix problems in program code, circuit layout, or crafting when an artifact does not function as intended (McCauley et al., 2008) is seen as being as important as their ability to generate the code, circuit blueprints, or crafting in the first place. Thus, examining how failures and solution generation in the process of debugging open-ended design projects are mediated by tools and materials can provide us with an important understanding of how failures have the potential to become productive opportunities for learning outside of well-defined problem spaces.

3. Context, participants, and data

3.1. Workshop participants

We conducted this study with 16 high school freshmen (7 boys, 9 girls, 13–15 years old) from a science magnet high school in a metropolitan city in the northeastern United States. A magnet school is a specialized school for students who show extraordinary aptitude in a particular area, such as science or the performing arts. Though it is a public school, students must go through an application process and be selected to attend. Students participating in this study reflected the overall demographic composition of the school, which is as follows: 56% Black, 19% Asian, 19% White, and 6% Multiracial. Participants selected our e-textiles workshop from a variety of workshop options as part of an immersion partnership between their school and a local science museum. The workshop spanned eight two-hour-long sessions at the museum and a ninth wrap-up session at the school. A researcher led the workshop and was supported by two graduate students who assisted with classroom observations and collecting data. In the workshop, students worked through a series of three e-textile projects of increasing technical and aesthetic complexity: 1) an

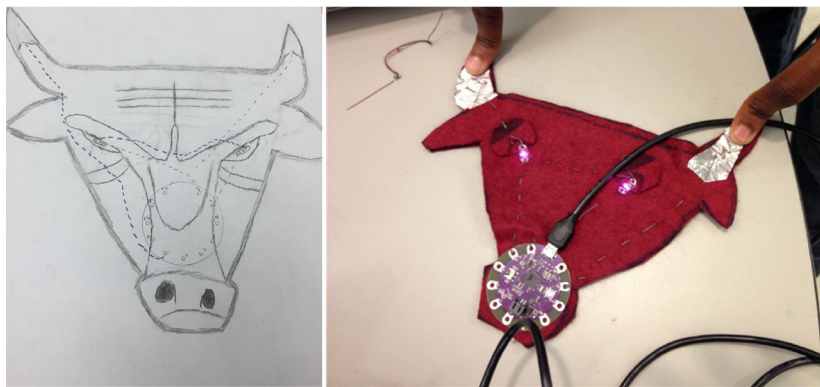


Fig. 1. Jordan's circuit diagram (left) and completed logo remix project (right).

introductory activity crafting a simple functional circuit with an LED light, coin cell battery, and conductive thread; 2) a starter wristband project with two LED lights, coin cell battery, conductive thread, and snaps (functioning as a switch) that closed the circuit; and 3) a more advanced 'human sensor project' described below in more detail (Kafai, Lee et al., 2014). The third project was the most complex as it required students to create a codeable circuit (Litts, Kafai, Lui, Walker, & Widman, 2017) within an open-ended design context.

3.2. E-textile design

We focused on students' design processes in the human sensor project (see Fig. 1), where students create two touch sensors out of conductive material that respond to being touched or squeezed by the human body and connect these to a LilyPad Arduino microcontroller. Once the LilyPad Arduino is appropriately programmed, when both sensor patches are touched simultaneously, the e-textile project responds with some form of interactivity, such as LEDs lighting up in a particular pattern. We imposed additional design constraints in the form a "Logo Remix" theme and a limit of three LEDs. Students' circuitry and code had to be integrated into a remix of an existing brand logo (e.g., their favorite sports team or brand). Each student created his or her own Logo Remix inspired by sports teams, bands, a favorite coffee chain, and clothing brands popular with teenagers. As an early phase of the design process, we instructed students to create a circuit design blueprint showing all of their electrical connections mapped onto their aesthetic design, which we reviewed before they began sewing. For instance, Jordan created a circuit diagram using red and black colored pencil to delineate positive and negative electrical lines (see Fig. 1). All students uploaded their design blueprints and received feedback via an e-textile website (the now defunct ecrafting.org) from graduate students who were more advanced in e-textiles. Feedback included comments on both the aesthetics and the function of the project. As students in the workshop moved forward with constructing and programming their e-textile project, the circuit blueprint represented one functional solution to the design challenge and served as their guide, even as they were forced to generate additional solutions due to unanticipated design challenges.

3.3. Data collection and analysis

To address our research questions about the debugging challenges students encountered and the solutions they implemented using the available tools, we collected a range of data on students' design processes focusing on challenges students encountered and resolution strategies they employed. In addition to documenting the progression of students' artifacts and code through photographs and screenshots, including the evolution of students' design blueprints, we kept extensive field notes throughout the workshop and interviewed students after they completed their projects. Interviews were semi-structured to capture their perceptions of challenges, or moments of failure, they encountered in their crafting, coding, and circuitry, and how they generated a solution for each challenge they shared. The interview protocol was specifically designed so that students would reflect back on moments of failure, which prior research has demonstrated is often at the points where crafting and circuitry or circuitry and coding intersect (Kafai, Fields, & Searle, 2012). For instance, short circuits caused by poor sewing (e.g. sloppy stitches, loose knot ends) are a common area of failure and debugging in novice e-textiles projects. Ten students were interviewed in pairs due to time constraints. Our main analysis focused on the student post-interviews, which we triangulated with field notes and photos of students' design processes.

Two research assistants coded all of the data and iteratively developed a coding scheme around challenges and resolutions. Initially, coders completed open line-by-line and in-vivo coding (Saldana, 2009) to get an overall sense of the data. Inspired by the productive failure literature, researchers then coded through a four-phase process: (1) Identified points of iteration/challenge (95 total); (2) Generated and applied a coding scheme of the types of challenges (e.g., knots/tangles, polarity of LEDs, etc.) remaining open to adding new codes; (3) Determined approaches to solution generation: alone, with a peer, with a teacher, or not at all; and (4) Clustered codes around larger themes. For instance, challenges like knots/tangles and stray ends identified in the second phase of coding are connected by the underlying challenge of crafting with conductive thread. The research team discussed and resolved disagreements or inconsistencies. One researcher applied the coding schemes for "challenges" and "resolutions" to the field notes to

triangulate with the findings from the reflective interview. No new codes were generated, but the fieldnotes further contextualized the strategies students utilized to remedy challenges. In our report of findings, we use pseudonyms for all participants discussed.

4. Results

Eagan, a student participant in the workshop, inspires our results section with her reflection on the benefits of working through multiple challenges: “Even though I never got one to light up (laughing)... I learned from my mistakes. I didn’t just, ‘oh I made a mistake, ugh, give up,’ but I learned from my mistakes” (Int., 5/08/15, p. 8). Whether or not failure occurs in ill-defined or open-ended problem spaces, it is clear that failures, which are often perceived as challenges, can become stepping stones to success. We focus our report of results on the two most commonly reported instances of failure in our data set: (1) students’ challenges working with conductive thread, and (2) students’ challenges in the design of spatial circuitry. Every student reported encountering both of these challenges in his or her human sensor project. This observation is consistent with prior work which identified that these two phases of the design cycle significantly impacted project development (Litts et al., 2017; Lui, Litts, Widman, Walker, & Kafai, 2016). As the two most complex phases of the human sensor design process, the tools and materials students use provide important physical feedback about the functionality of their projects.

In post-interviews, six out of 16 students reported that they did not successfully complete their project (e.g., they had not finished sewing or did not upload their code to their LilyPad). All students reported moments of failure at some point in the design process, and in these moments they generated both successful and unsuccessful solutions. The majority of students reported working on their own to troubleshoot and debug their projects without direct instruction. While it is likely that students received more external help than they reported, what is important is that they persisted in solution generation even if they did not produce fully functioning and finished products. Working with conductive thread and designing spatial circuitry were not only the two most common challenges but also illustrate students’ successes in persisting through failure, as students discussed in their reflections on their own design processes.

4.1. Productive failure in crafting with conductive thread

Data analysis highlighted a number of moments of failure or challenges for students, including project time constraints and working in the programming environment, Arduino. Together, the two most prevalent challenges (working with conductive thread and designing spatial circuitry) accounted for 68 out of 95 (roughly 72%) of all statements about failure in the interviews. In what follows, we explore what these challenges looked like from students’ perspectives and highlight the process of failure and solution generation within two problem spaces, crafting with conductive thread and designing spatial circuitry.

4.1.1. Experiencing failure in crafting with conductive thread

Learning to design and make e-textiles is not just about crafting skills, which are challenging in their own right (Lee & Fields, 2013), but also about how these skills intersect with circuitry knowledge in a domain specific way (Litts et al., 2017; Pepler & Glosson, 2013). For novices who have not fully grasped the properties of conductive thread, however, it often appears that crafting and circuitry can be separated out as discrete entities, resulting in failure to complete a functional circuit. In our analysis, crafting with conductive thread accounted for 28% of the total challenges faced by students. Kerry shared her reflection on some of her sewing challenges:

Oh! Let’s do all the problems I went through. Hey...so when you wanna start [thread] the needle, it doesn’t want to go in. And then when you finally get it in, you have to make a knot. And the knot doesn’t wanna be formed. So, then you finally make the knot and you’re sewing, and sometimes...either the knot and the entire thread comes through and the needle just disappears and the thread’s left there alone, or, you know what happens? Knots come out of nowhere when you don’t need them! It’s like, hey, where were you when I was trying to knot you? (Int., 6/19/15, pp. 4–5).

In this reflection, Kerry highlights several of the ways in which she experienced failure in the process of crafting her e-textile project, including difficulty threading the needle, difficulty tying knots in appropriate places, and the propensity of the thread to tangle easily. Rhett, an inexperienced sewer, experienced a different but related problem when he tried to connect components with one giant stitch rather than many small ones. He explained, “often times I forgot to do a running stitch and I would just put it straight there and that was frustrating because I had to cut it and try again” (Int., 5/11/2015, p.2). These large stitches were easily pulled loose and failed to hold the components in place. They could also move around and touch other lines of conductive thread, creating unanticipated circuitry problems like short circuits. As Kerry and Rhett illustrate, these basic sewing challenges were especially frustrating and became even more frustrating for students when they realized that, because of the uninsulated, conductive nature of the thread, sewing mistakes and circuitry mistakes were often intertwined.

All students had short circuiting issues in which their positive and negative threads tangled together or were connected by stray ends of thread and many students discussed having to repeatedly cut out and re sew lines of thread because of incorrect or crossing circuitry. Taraji, an experienced sewer who often mended her own clothing outside of school, remarked that she liked the thicker feeling of the conductive thread, but even she admitted that it was difficult, “getting to understand, like, sewing without making the thread in the back like touch, or going over other [threads]” (Int., 5/08/15, p. 3). In this case, activating prior knowledge about sewing may actually be counterproductive because conductive thread behaves differently than non-conductive thread, suggesting that it is useful to integrate feedback provided by the tools and materials themselves.



Fig. 2. Mack's project partially complete, front with LEDs (left) and back with beads (right).

In addition to the material properties of conductive thread, students also experienced failure in terms of where they sewed their circuit to, such as using conductive thread to connect the positive side of a LED to the negative ground on the LilyPad Arduino. For instance, Sabrina recalled, “another challenge was connecting it to the wrong LilyPad circuit. I messed that up, like, I know when I first did it I didn’t connect it to the negative and that messed up my whole project” (Int., 5/08/15, p. 2). In these ways, students experienced multiple failures related to crafting with conductive thread in the context of their e-textiles projects.

4.1.2. Solution generation in crafting with conductive thread

A large part of resolving challenges of crafting with conductive thread is activating prior knowledge about circuitry (learned in the two projects prior to the human sensor project) to see how crafting causes short circuiting. Students must understand that because the thread is conductive (and not insulated) it cannot cross and their stitches must be tight to ensure strong connections. Students largely worked by themselves (55.6%) to troubleshoot challenges of crafting with conductive thread, but some required teacher (29.6%) support, and a few solicited peer support (7.4%) or were not able to resolve their challenges (7.4%).

Working individually, Mack realized the importance of solid connections, but struggled to sew accordingly, so he generated a creative resolution that led to successful circuitry. He expounded, “The hardest part was connecting the LEDs to the thread, because if I would stick it in, I only did it single [thread] so it would pop [break] and then I had to restart” (Int., 5/08/15, p. 2). In response, he sewed plastic beads behind the LEDs to guide his sewing on the back of his project and secure his components (see Fig. 2). In this way, using a guide bead becomes an example of successful solution generation using the available tools and materials and the feedback provided by the conductive thread. Other students resolved this particular challenge by taking more traditional approaches like trimming their stray ends to prevent short circuiting with thread crossing in the back.

Likewise, Kerry described how she resolved the issue of short circuiting caused by stray ends, “I did that on my own after I was given tape. Because I saw and I was like, oh, you know, this part is so long and then [the teachers] just placed tape down on the table and so I was like, ok and decided to tape things” (Int., 5/08/15, p.7). While Kerry believed that she resolved this challenge on her own, she also illustrates how minimal, implicit teacher support (placing the tape down on the table) structured her ability to generate a successful solution using the available materials. In contrast, Jonathan needed direct teacher support to tackle a short-circuiting issue he was having with stray ends. He recounted, “I had to trim down a bunch of stuff in the back so that they didn’t cross over...I had to be told that’s what I had to do” (Int., 5/08/15, p. 3).

In other cases, students solicited help from their peers. For instance, Kendra described how her friends helped her make a proper running stitch, “Well previously my threads were really far apart, and then my friends...noticed that it could like really be easy to get loose...So they told me to make my threads tighter, so it’ll be like difficult to [get] loose and they wouldn’t be tangling. That was a helpful suggestion, so I just sewed tinier” (Int., 5/11/15, p. 6) Unlike traditional sewing where typically only one side of the project is important, both sides of e-textiles project are equally important for aesthetics and circuitry. In this way, e-textiles run counter to most individuals’ prior knowledge about the back of a sewing project.

While we instructed students to secure their components by sewing the connection at least three times, several students still faced challenges with this technique. Kendra explained, “This [LED] is pretty loose. I didn’t sew it tight enough, and it’s pretty dull, too. So, I don’t know, those could be contributing factors [of] why...it doesn’t really light up that much” (Int., 5/11/15, p. 2) Kendra struggled to understand *why* securing her components was important until she made the mistake herself, and though she left this problem unresolved, she articulated the most likely cause of her dim LED light in her reflective interview. Kendra’s struggles with an LED that is both poorly sewn (loose) and dim highlight the gaps in her knowledge of circuitry and its intersection with craft. However, the potential solution, sewing the LED more tightly, that she articulated in her reflective interview illustrates growth in her knowledge of the intersections of craft and circuitry in e-textiles design.

4.2. Productive failure in spatial circuitry

In addition to experiencing failure related to an incomplete understanding of the properties of conductive thread as connected to circuit design, students also experienced failure related to *spatial circuitry*, the design and physical construction of the circuit. In fact, spatial circuitry accounted for 43% of all challenges (41 out of 95). Spatial circuitry is not just about making sure that lines of conductive thread do not cross or that the whole project fits on a sheet of felt, but also takes into account making sure that the correct



Fig. 3. Kerry's circuitry blueprint and partially completed project, front (left) and back (right).

circuit components are connected to the correct ports on the LilyPad, since not all ports, for example, can read input from a sensor.

4.2.1. Designing spatial circuitry

Although we required students to first draw a paper and pencil representation of their design (including tracing the LilyPad and its ports and labeling the components), which we call a design blueprint, and to consult with one of the instructors before moving onto constructing their design, translating the circuitry blueprint into a physical artifact proved challenging in terms of both functional and aesthetic considerations. As Kerry recounted in her reflective interview, the placement of various design components often evolved through a degree of failure in the construction process (see Fig. 3). She said:

When I did [my project], I had to switch [the patches] like four different times and I also had to switch my LEDs because the way that my design worked is...there wasn't a lot of space over here or through here [pointing to top of her project] so it was like, you had to try to cut through things and...hide some things but not a lot. And I was like trying to make everything be there but not touch and it was really confusing...LEDs had to switch and ideas had to switch" (Int., 5/08/15, p. 11).

In this reflection, Kerry highlights several common aspects of spatial circuitry that challenged students, including the size, shape, and placement of their conductive patches and also an aesthetic desire to hide some of the circuitry while still having a functional project. Kerry's closing comment that not only the placement of the LEDs had to switch, but also her ideas highlights the ways in which failure and solution generation can foster creative problem solving. Similarly, Taraji explained, "I didn't really estimate all the amount of space I would have on the felt [as opposed to the piece of paper]. So, when I actually started sewing on the felt I had to like think, like before I got to put my conductive patches on I had to think like how big they could be, or where exactly they could fit" (Int., 5/08/15, p. 4). Across projects, students experienced failure related to realizing their design goals within the constraints of their circuitry and coding knowledge.

4.2.2. Designing codeable circuitry

In spite of the challenges students faced in translating their paper and pencil design blueprints into a physical reality, many referenced their original design blueprints or created multiple versions of their design blueprints in order to resolve challenges related to spatial circuitry. These are akin to generating multiple representations and solutions in a productive failure design for a more well-defined concept. More than half of the students (58.5%) relied mostly on themselves to solve challenges related to spatial circuitry, but nearly one third (31.7%) requested teacher assistance to troubleshoot their circuitry. Only one student reported soliciting peer support (2.5%) and a few were unable to resolve their spatial circuitry issues (7.3%).

Students who worked to resolve their spatial circuitry problems often reported generating multiple design blueprints, or possible solutions, along the way. Taraji, for example, reported a careful planning process, "Before I would actually sew, I'd draw the pattern out and make sure none of them like crossed each other, and once I had that I'd just copy it off the paper and to the actual [felt]" (Int., 5/08/15, p. 3). Each time Taraji made changes to her design plan she modified her blueprint to match. Taraji's proficiency in using her design blueprint streamlined her overall design process, as she described, "I just followed each step that was listed on here and it was pretty simple" (Int., 5/08/15, p. 4). In other words, Taraji was able to activate her prior knowledge and generate a solution that allowed her to consolidate what she had learned. In contrast, Kerry attempted to work through spatial circuitry challenges by making in-the-moment changes. In her reflective interview, she recalled:

The touch sensors, they were supposed to be...I have this right here, I have the basic idea (showing design blueprint). My design never changed, it's just the way I did it, I switched it. Like I had these were gonna be the conductive touch sensors (showing cheek on design blueprint), because these were gonna be touch sensors and they were supposed to go right here on the edge (pointing under the eyes), but you see how close they are to the eyes and everything it made everything a lot harder to navigate so things got weird" (Int., 5/08/15, p. 11).

Since Kerry did not reflect the changes to her spatial circuitry on her design blueprint, she failed to realize that her design iterations would result in crossing negative and positive threads, which caused a lot of frustration, because she "had to do redo everything" (Int., 5/08/15, p. 12). Rather than entering a consolidation phase, Kerry continued to explore solutions in-the-moment. Both Taraji and Kerry resolved their spatial circuitry challenges on their own, however they used different strategies and this resulted

in different outcomes. Taraji successfully tackled her spatial circuitry challenges and created functional circuits, while Kerry unsuccessfully tackled her spatial circuitry challenges by attempting in-the-moment changes which resulted in short circuits. Here, there is a canonical solution in that there are rules of how circuitry works that need to be followed, but there are multiple ways to navigate the process and the spatial layout of the circuits in relation to the aesthetic design. Because each design is different in where the components are placed, there is no one correct solution for questions of spatial circuitry.

Students also requested teacher assistance to troubleshoot their spatial circuitry challenges. Eagan, for example, described her biggest mistake, “Well the circuiting obviously. Cuz I just kept messing on up, but yeah I had great teachers help me out” (Int., 5/08/15, p. 8). She further explained that, with teacher support, she tried rotating the orientation of her Lilypad within her design and that helped resolve a lot of her issues connecting her LEDs and touch sensors to the Lilypad without crossing positive and negative lines. Another student, Jess, reported assisting her friend with connecting her LEDs to the Lilypad, “I was helping Lauren with stuff, because she didn’t know where to connect it” (Int., 5/11/15, p. 5). Even though Jess struggled herself with the concept, she understood the challenge of thinking through, “how [the] design will fit into the circuitry... [and]... not to get the thread all tangled up in each other” (Int., 5/11/15, p. 6). A few students, like Mel, didn’t reach out at all: “Since we don’t know anything about this part, this Lilypad [small computer], I don’t know where to put which...I don’t know, where to put things and stuff. So, or how it works, cuz I don’t know how this thing works... it’s just really confusing” (Int., 5/11/15, p. 5). Even at the end of the project Mel still struggled to understand the importance of her design blueprint and the function of the Lilypad, but did not report asking for help to resolve her confusion with these concepts. While in the productive failure literature, students with less prior knowledge were still fairly capable of generating solutions, the more open-ended nature of the e-textiles project raises some questions about how the available tools and materials facilitate the activation of students’ prior knowledge and when failure within open-ended design tasks is productive.

5. Discussion

By combining Kapur’s (2008) conceptualization of productive failure with an understanding of the role of construction in learning (Bruner, 1973; Papert, 1980), we contribute to the growing body of work on failure as a lens for understanding and supporting the learning that takes place in open-ended, material-based, and computationally-rich design activities. Drawing upon an examination of students’ perspectives on experiences with failure and solution generation using e-textiles tools and materials, we argue that failure is always present in open-ended design tasks, especially because multiple solutions exist. In the following sections, we discuss how our findings extend existing work on productive failure and contribute to our growing understandings of how to design for more productive failure in open-ended design tasks. Finally, we explore directions for future research.

5.1. Productive failure in well-defined versus open-ended tasks

Most research on productive failure as a learning design has occurred in the context of math and science activities where the process of generating solutions to ill-structured problems facilitates the activation of learners’ prior knowledge in service of later solving a well-structured problem. However, in open-ended design tasks there is not a clear two-phase process moving from solution generation to consolidation of knowledge. Instead, learners face multiple solutions that can target many interrelated concepts at once (Goel & Pirolli, 1992).

Our findings contribute to the productive failure literature by suggesting a place for manipulables and construction processes within the solution generation phase. For instance, e-textiles designs require integration of knowledge from multiple domains such as (crafting, circuitry, and coding). Indeed, the two most common challenges students reported encountering involved the behavior of conductive thread and spatial circuitry, both of which exist at the intersection of craft and circuitry. Our findings suggest that, in some cases, the available tools and materials guided the open-ended design process in ways similar to the role of problem structures and canonical solutions in more constrained productive failure designs. For instance, when Rhett’s stitches kept pulling out or causing short circuits, he knew that they were too big and he needed to rip them out and sew smaller stitches. Similarly, Taraji created a new design blueprint every time she needed to alter her circuitry and then translated her blueprint into a sewn artifact. In these ways, we see students drawing upon the available tools and materials to negotiate failure in the e-textiles context. Another example is Mack’s creative solution of using beads to guide his LEDs and secure his components, which illustrates the productive nature of repetitively making the same mistake. In open-ended designs, there is not a parallel canonical solution to which students can compare their self-generated solutions. While there are “right” and “wrong” ways to sew a circuit or write syntactically correct code, there are multiple pathways, which could be categorized as “better” or “worse”, to arrive at a correct solution, drawing on a range of design styles and techniques to find the ones best-suited to the particular aesthetic and technical demands of an individual project. Hence, while it is difficult to model a well-structured task like the one used in productive failure studies, our findings suggest that the available tools and materials may play an important role in understanding how failures can become opportunities for learning outside of well-structured learning designs.

Another contribution of our work to understanding failure in open-ended design tasks is the incorporation of students’ perceptions of failure and its role in the design process. By examining students’ perceptions of failure, we can better understand how and where to support failure as a productive enterprise in open-ended design tasks. While observations of e-textiles debugging illustrate the challenges that students face in completing their artifacts, understanding how students think about failure and solution generation in this context allows us to better design instructional supports for failure. Such retrospective accounts of students’ perspectives are rare in the current research on productive failure, which has mainly focused on examining the impact of different conditions on students’ learning outcomes. Understanding what students consider moments of failure in the design process, as well as how and where they

deal with failure through solution generation provides critical insights for designing supports in learning tools and interactions. By looking at failure as a productive rather than counterproductive dimension of learning, especially in open-ended design tasks, we can shift pedagogical directions as well as students' perceptions of such events that are not only inevitable in the design and learning process but also have been shown to foster creative problem solving. Indeed, research on creativity in design among both expert practitioners (Dorst & Cross, 2001) and design students (Christiaans, 1992) suggests that creativity in design emerges from a co-evolution of the problem and the solution over multiple iterations (Maher, Poon, & Boulanger, 1996). The work reported here lays the groundwork for more strategically supporting failure and solution generation in open-ended design tasks, such that failure becomes an opportunity for learning.

5.2. Supporting failure in open-ended design tasks

Some students in our study were able to move through exploration and consolidation phases of productive failure based on feedback from the artifact they were building, while others required additional supports, such as the help of a teacher or a friend, and a few others couldn't even begin to generate solutions. Research suggests that individual students engaged in traditional productive failure learning fare better than their peers receiving either direct or guided instruction (Kapur, 2015). Our findings suggest that in open-ended learning environments, guided instruction or other instructional supports could be beneficial for learners. For instance, in previous design studies, such guided supports have taken the form of reflections or design diaries (e.g., Kafai, 1995; Roth, 1998) to help novice designers with completion of their artifacts, alone or together.

In the case of e-textiles, we have collected data about the common challenges faced by novice learners which can provide input for a toolkit of solutions. It might be helpful to engage students in a more well-structured solution generation and knowledge consolidation process, such as in structured debugging or deconstruction tasks (Fields et al., 2016; Griffin et al., 2012). Such a two-phase approach could facilitate their solution generation and ability to learn from failure in open-ended design tasks. We hypothesize that such a process would further activate students' prior knowledge and create something akin to a consolidation phase. In these ways, our work contributes to growing understandings of how to design for productive failure in open-ended design contexts without compromising the affordances of the ill-structured nature of the task for creative solution generation.

6. Conclusion

While this study makes a contribution to the productive failure literature by analyzing students' perceptions of experiences of failure and solution generation in open-ended design tasks, future work needs to more closely investigate students' debugging processes to wholly capture the range of problems encountered and solutions generated. Doing so will allow us to more fully apprehend how students' learning processes incorporate solution generation and consolidation of knowledge. This may require moving beyond students' reflections on failure to assess what they actually learned. It may also require assessing learners after each phase of e-textiles rather than just after making their human sensor projects. Further, we must extend our investigation of failure in a materially and computationally rich environment. Our study suggests that, in some cases, the physical artifacts students make and the rapid feedback they provide about functionality can guide their problem solving with little to no teacher intervention. Thus, physical artifacts may an additional form of guidance to consider in future productive failure learning designs.

Acknowledgments

This material is based upon work supported by the National Science Foundation (IEST-1509245) to the third author. The views expressed are those of the authors and do not necessarily represent the views of the National Science Foundation, Utah State University, or the University of Pennsylvania.

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