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Stitching Circuits: Learning About Circuitry Through E-textile Materials

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Abstract Central to our understanding of learning is the relationship between various tools and technologies and the structuring of disciplinary subject matter. One of the staples of early science education curriculum is the use of electrical circuit toolkits to engage students in broader discussions of energy. Traditionally, these concepts are introduced to youth using battery packs, insulated wire and light bulbs. However, there are affordances and limitations in the way this toolset highlights certain conceptual aspects while obscuring others, which we argue leads to common misconceptions about electrical circuitry. By contrast, we offer an alternative approach utilizing an e-textiles toolkit for developing understanding of electrical circuitry, testing the efficacy of this approach for learning in elective settings to pave the way for later classroom adoption. This study found that youth who engaged in e-textile design demonstrated significant gains in their ability to diagram a working circuit, as well as significant gains in their understanding of current flow, polarity and connections. The implications for rethinking our current toolkits for teaching conceptual understanding in science are discussed.

Keywords Circuitry · Conceptual understanding · E-textiles · Toolkits · LilyPad Arduino

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Introduction

Central to our understanding of learning is the relationship between various tools and technologies and the structuring of disciplinary subject matter. Papert, for example, invited closer investigation of the specific tools we have available (i.e., "objects to think with") as they highly impact our ontological perspectives (1980). One disciplinary area that frequently utilizes tools toward the concretizing of abstract concepts is science education. One of the staples of early science education curriculum is the use of electrical circuitry concepts to engage students in broader discussions of energy (Tasker and Osborne 1985). Traditionally, these concepts are introduced to youth using particular tools—battery packs, insulated wire, nails, thumbtacks, paper clips, bulbs and so on—that help lay a foundation for more sophisticated forms of robotics, computing and engineering. However, there are affordances and limitations in the way that all tools highlight certain conceptual aspects while obscuring others, which has important implications for learning.

Overlooked in this landscape are more recent, commercially available tools for circuitry creation that integrate non-traditional conductive materials such as textiles, LEDs, conductive thread, Velcro, buttons and snaps. Though traditionally left out of circuitry introductions in science classrooms, these materials are crucial to a new movement within engineering and computer science; specifically, opening up new avenues of research that have led to innovations in wearable computers with applications in fashion (Berzowska 2005), healthcare and military defense sectors (Ullah et al. 2009). A commercial innovation that has brought these materials to educational circles is the LilyPad Arduino, a toolkit designed for novices' and professionals' e-textile productions (Buechley et al. 2008).

The LilyPad and related power supplies, sensors and actuators can be sewn to fabric using conductive thread. Recent research advocates the LilyPad and e-textile toolkits more broadly as being able to allow designers to investigate aspects of circuits that are otherwise invisible to the user (Buechley 2010; Kafai and Peppler in press; Peppler and Glosson in press). In e-textile productions, the fabrication of stitches and circuits reveals the underlying structures and processes in tangible and observable ways. Given the growing number of educators that have an interest in bringing these materials into the classroom, we sought to explore whether the visibility inherent to these materials could prove significant for youths' conceptual understanding of electrical circuits.

To test whether these materials were instructionally sound to bring into the classroom, our study sought to explore whether the use of an e-textile toolkit could aid youth in learning about electronics in an elective setting, as well as whether e-textiles could elucidate important circuitry concepts that traditional materials have historically struggled to convey. To do so, we invited youth (aged 7–12) at a local Boys and Girls Club to learn more about electrical circuitry and design a host of e-textile projects in the course of a 20-h afterschool workshop. We evaluated gains in youths' understanding of circuitry concepts through assessments at the start and end of the workshop, upon which we ran tests of statistical significance to determine whether youth had significantly gained in their ability to diagram electrical circuits. Furthermore, we sought to uncover how the materials promoted discussion between peers and instructors. Results indicate that workshop youth significantly gained in their understanding of current flow, connections and battery polarity, as well as in their ability to diagram and create working circuits in the process of designing with e-textiles. This work seeks to provide a foundation for integrating e-textile materials into standards-based practices in formal education systems and to illustrate how this might be taught and assessed in the classroom.

Background

Electrical circuitry in the National Science Standards is included as part of a broader investigation of energy within the Physical Sciences. As part of this investigation, the National Research Association emphasizes inquiry through making and experimentation; through not only hands-on experiences but "minds-on" experiences as well (National Research Council 2012). By extension, it is not enough to follow a series of steps to build a working circuit if one does not grasp the concepts at play that make the circuit operate. For example, a simple light bulb, commonly used in early science education circuit experiments, can be quite confusing as the negative and positive terminals are hidden or invisible to the child in a twisted silver shape. The same "invisibility factor" holds true for a socket or even some types of batteries. Attention paid to the amount of transparency afforded by the project types and tools used in science education activities can prove beneficial for eliciting the "minds-on" experiences denoted in the National Science Standards.

Leveraging new materials to inform youths' understanding of electronics is especially prescient given the historical prevalence of youths' conceptual misunderstandings of simple circuitry (Evans 1978; Tiberghien and Delacote 1976). Through a series of circuit diagrams and interviews, Fredette and Lochhead (1980) probed for incorrect perceptions held by undergraduates enrolled in introductory physics and engineering courses and looked for the root of their misconstructions of how circuitry works, ultimately determining that schools needed to be more explicit in their instruction of a circuit's "'passing-through' requirement" (i.e., that all elements of a circuit require voltage to pass through an IN and an OUT terminal) in early physics education. However, to do so, means more than lucidly illustrating the anatomy of each component in a circuit—an electrical power source, a load and some wire to connect them in the most basic configuration—but also the fundamental concepts of how these components interact with each other; namely *current flow* (Osborne 1981, 1983; Shipstone 1984), battery *polarity* (Osborne et al. 1991) and circuit *connections* (Osborne 1983; Shepardson and Moje 1994; Asoko 1996). In the following, we give an in-depth explanation of each construct and their application to e-textile tools and materials.

One of the central concepts explored in prior research has been battery *current flow*, traditionally defined as a current (i.e., flow) around a circuit (i.e., following one of the simple circuit current models) (Osborne 1981). We have adapted the term *current flow* within the context of e-textiles as making a loop with the sewn lines and components with no redundant lines (i.e., stitching lines) or instances of shorts (i.e., loose threads touch the opposite terminal line). Osborne's early work in the Learning in Science Project (LSP) investigated children's ideas about electrical circuits and current flows (1981) using a technique developed called the "interview about instances" approach (Osborne 1980). This approach allowed the researchers to probe the student for conceptual understanding using a card set of 20 simple drawings (instant or non-instant of the particular concept) while asking the student to first categorize the card then explain why the categorization was made. The LSP found that youth held three views of the current flow: A: unipolar (i.e., no current in return path), B: bipolar or clashing (i.e., current runs paths from battery to bulb) and D: scientific (i.e., equal current in both paths), but in a 1982 study with youth age 8-12, a fourth model emerged, C: where the bulb uses up the current, therefore less is returned to the battery (see Fig. 1) (Osborne 1983). Important to this form of testing is the relationship between representations of the tools and materials and the use of professional circuit diagrams created by the researchers (as opposed to the children) as a probe for understanding.

To learn more about participants' procedural understandings of circuitry, Osborne et al.' (1991) electricity report in the Primary Space Project tasked children with drawing their own simple circuit diagrams that featured a battery, light bulb and their connections based on their understanding of circuitry. Though the diagrams varied in approach (e.g., some diagrams exhibited lines connected directly to the glass bulb, while others showed two connections to the bottom tip of the bulb, as well as other common mistakes), the majority of children's diagrams were based on faulty logic. An additional study observed that when complications arose when the return path to the battery was not obvious (e.g., flashlight), children hung onto their unipolar model of current flow, even though most children's views of the three circuit parts (e.g., battery, LED and wires) had changed (Osborne et al. 1981). With the majority of research using hard materials in the circuit construction kit (e.g., batteries, wire, motors, fans), along with a light bulb, where a negative and positive terminal is essentially hidden, we would argue that invisibility in parts not only interferes with understanding of current flow but also with student understanding of polarity and connections in circuits.

Polarity, a term often included when discussing connections, occurs when the proper battery terminals are connected to the proper LED terminals in a simple circuit. The 1991 Electricity report used a concept like polarity as one of the four main issues to research defining the area as "the necessity for any circuit to have two connections to a device and an electrical power source" (Osborne et al. 1991, p. 43). However, this definition falls short when using LEDs or other uni-directional components in the electrical circuit. In the context of e-textiles, the orientation of the LEDs (and many other components) in relationship to the power source is crucial to creating a working electrical circuit. In other words, the minus terminal of the battery must flow in the minus of the LED and, likewise, the plus terminal of the LED must be connected to the plus terminal of the battery in order for the LED to be illuminated.

In previous circuitry literature, the term *connection* pertains to the joining of electrical parts to form a working circuit, thus lighting the bulb (Osborne 1983; Osborne et al. 1991; Shepardson and Moje 1994). Some prior studies have found that youth had trouble creating working circuits when using the battery and bulb models (Osborne 1983). Additionally, in 1991, the Primary Space Project Research Report on Electricity found "it may not be helpful to start teaching electricity with bulbs where the two connecting points are not obvious" (p. 58). We believe this adds support to our argument for a new toolkit with visible terminals to aid in the appropriate connections being made for a working circuit. While, traditionally, researchers have defined connections as the joining of the battery, bulb and wires to form a working circuit (Osborne 1983), we have adapted the term within the context of e-textiles to define connections as the craft of the circuit. That is, the lines (i.e., conductive thread) successfully connect one component to another with attention being paid to the particular points of conductivity (i.e., looping the conductive thread through the terminal hole for a strong connection).

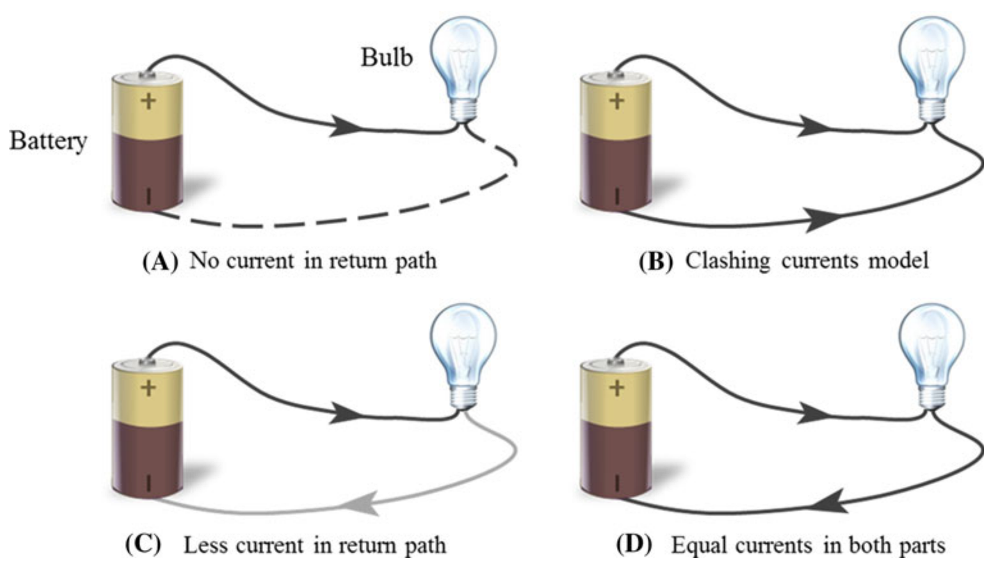


Fig. 1 Adapted from the original, illustrating four different models of current flow in simple circuits (Osborne 1983)

Methodology

This study took place during the summer of 2010. The 20-h elective curriculum contained pre- and post-tests to examine participants' understanding of circuitry including current flow, connections and polarity. A sequential mixed methods approach (Creswell 2009) were used, combining both quantitative and qualitative methods including a pre- and post-test design with paired samples, as well as qualitative data collection to provide a comprehensive analysis. Three case studies were used to provide a more detailed analysis. Qualitative data primarily focused on the collection of youths' surveys, interviews, journals, artifacts, as well as videotaped observations. The coding schemes were created using a priori codes.

Research Questions

Our primary aim for this study seeks to understand if youth develop a conceptual understanding of simple circuitry while constructing electronic artifacts using an e-textiles toolkit. Specifically, we asked

1. How can youth learn about electrical circuits in an elective environment?
2. How can e-textiles elucidate the important concepts in electrical circuits that traditional materials have historically struggled to convey?

Setting and Participants

During the summer of 2010, we held an e-textile workshop at a local Boys and Girls Club (BGC) in the downtown district of a midsized, Midwestern city. At the time of the study, the BGC consisted of over 200 youth, 39 % of which were African American/Latino/Asian and 61 % were White. These youth ranged in ages from 6 through 18 years old and more than 80 % were from low-income homes that were unable to pay the $20 annual fee.

Youth signed up for the two-week e-textiles workshop on a voluntary basis; no prior experience with circuits or sewing was necessary. While 27 youth initially signed up for the workshop (consisting of 9 females and 18 males with ages ranging from 7 to 12 years), we focus on 17 youth who participated in the entirety of the workshop, including being present for both the pre- and post-tests ($n = 17$). This group consisted of 5 females and 12 males, and had an average age between 9 and 10 years. The workshop was led by five members of the research team and one BGC staff member to aid with the Club culture and norms.

Because learning about circuits is common within school, we surveyed youth to assess prior experience with circuitry and electricity from their school and home experiences, asking 'Have you learned about circuitry or electricity in school or at home? If so tell us about it'. While the majority of youth had no prior experience, six of the youth (three males and three females) revealed that they had some prior experience with traditional materials. However, no one was able to recall specific content about circuits, only general descriptions or the environments in which they learned them (e.g., the local science museum, or "4th grade").

The E-textiles Workshop

The 20-h e-textile curriculum was administered at the Club over a period of two weeks at an average of 2 h per day while schools were out of session for the summer. The majority of the workshop consisted of youth working on e-textile projects, interspersed with three 20- to 30-min informal presentations on foundational concepts (i.e., Day One: overview of how electronics were being used in fashion, entertainment and gaming; Day Two: introduction to simple circuitry and the foundations of electronics; and Day Eight: laying out circuits in parallel or in series configurations). A concerted effort was taken to keep didactic modes of instruction to a minimum—the majority of youths' learning, we hoped, would come from playful exploration with the materials and observations of each other's projects and processes.

The hands-on activities throughout the workshop consisted of a range of projects, including constructing a circuit on a paper airplane or origami crane with wing tip LEDs (Day 1); connecting circuit elements via alligator clips to form simple and parallel circuits (Day 2); practicing running stitches on sample sheets of paper (Day 2); designing and constructing simple circuit quilt squares (Days 3–4); designing and sewing a t-shirt LED circuit (Days 5–6); sewing a Persistence of Vision (POV) Wrist Band with five parallel LEDs and a LilyPad Arduino, which involved, though not discussed for the purposes of this article, youth adding computation to their designs (Days 7–10). These project types were preselected by the youth through an informal survey prior to the start of the workshop.

Tools: The E-textiles Toolkit

Youth had access to a range of materials throughout the workshop, including traditional and LilyPad LEDs, LilyPad button boards, coin cell batteries plus holders, conductive thread, in addition to a number of textile and craft materials (see Fig. 2). For each project, limits were set on the number of components that could be sewn into projects

Fig. 2 LilyPad E-Sewing Kit: conductive thread, battery holder, 3 V coin cell battery, push button switch, light emitting diode (LED)

to help ensure alignment between project complexity and the youths' abilities.

Each LilyPad part contains a conductive sewing ring of metal which extends through the part's physical hole in the plastic piece onto the back side where the ring resembles the front ring. There is also a conductive tip or pad on the front side only, one for each of the terminals (See Fig. 3). Just as in soldering, the objective in e-textiles is to create a solid joint; if a solid connection between the wire–or in our case, the thread–and the metal is not made, there is a weakness.

To help situate the reader to this new field, we highlight a sample project that youth produced in this workshop: the Electrici-Tee with a simple sewn circuit and one LED.

The Electrici-Tee: Simple Circuit T-shirt

Each t-shirt circuit was first designed by the youth in their journals and checked by an adult team member for any working circuit issues as well as design complications (e.g., crossing negative and positive threads, sewing the entire length of the t-shirt). Next, youth placed stickers on their shirts of the three components: the battery holder, the LED and the switch, to help visualize where the conductive thread would need to be stitched to connect the elements. The stickers were swapped out for the corresponding electronic part at each phase of the sewing process (see Fig. 4). Youth stitched the thread onto their shirts themselves by hand and were encouraged to ask each other or an adult for assistance if they ran into debugging problems. Youth personalized their projects not only through the selection of the one-of-a-kind t-shirt but with incorporating different LED colors, LED placement, construction of handmade switches and hand drawn designs on the t-shirt. The youth wore their finished projects and enjoyed using their conspicuous or inconspicuously placed switches to turn the LEDs on and off.

Data Sources

Over the course of the workshop, we collected various data sources, including pre- and post-assessments, youths' workshop artifacts and videotaped observations.

Pre- and Post-circuit Diagram Assessment

At the beginning of the implementation, youth were given a pre-test to assess their knowledge of basic circuitry using circuit diagrams, testing specifically for whether youth could create an overall working circuit, but more specifically, whether they understood three core concepts: current flow (i.e., completed circular paths with no redundancy or shorts), connections (i.e., completed lines successfully connecting one component to another and attention paid to the particular points of conductivity), and polarity (i.e., being mindful that the battery and LED have a plus side and a minus side).

In our review, we discovered that circuit diagrams and accompanying assessments are traditionally rooted in the materials in which the learner uses in the process of developing conceptual understanding. In our context, however, we moved from using traditional electric circuit drawings that use light bulbs and batteries to draw upon pieces from the LilyPad e-textiles sewing kit (e.g., battery holder, LED and switch). Using parts that would be familiar to youth in the workshop, we administered both tests with LilyPad part stickers marked with clear positive and negative terminals, tasking the participants to create a functioning circuit from the available parts by drawing lines between the appropriate terminals (see Table 1).

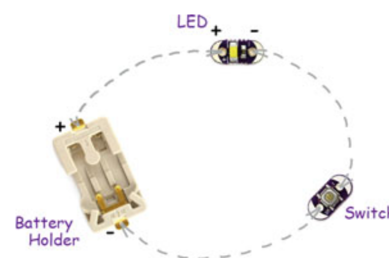
Videotaped Observations

Two to three cameras with high-quality wireless microphones were used to capture the daily workshop events and

Fig. 3 LilyPad LED illustrating conductive surfaces

Fig. 4 T-shirt drawing and finished product with working circuit, handmade cloud switch and hidden battery holder inside the shirt

Table 1 E-textile test text, parts stickers and sample of possible solution

Instructions	Stickers	Sample working circuit solution
Using the stickers stapled here (battery holder, LED[s] and switch), build a working (closed) electrical circuit. Use your pencil to draw any of the connections for a working circuit		

dialog. The cameras were focused on particular small groups of individuals over the course of the workshop, picking up about 3/5 of the activities and discussion of the small group at the particular table. In addition, all large group discussions were videotaped, as well as science demonstrations and activities. In sum, we gathered 42+ h of video footage that was subject to further analyses.

Workshop Artifacts

Youth work was photo-documented in their various stages of development on a daily basis (though completed artifacts were taken home by the participants at the end of the workshop). Additionally, youth design journals were collected, which contained all of the participants' notes, as well as their circuit diagrams, initial designs and finished project sketches. Youth often used preprinted part stickers in their journal and on their artifact during the design stage to assist in the identification of terminals.

Analytical Techniques

Analyzing the Circuit Diagram Assessment

The Circuit Diagram Assessment was analyzed by coding the youths' responses on a 1-point scale. In developing the coding scheme, we wanted to examine individual aspects of the circuit beyond whether it was working or not. Therefore, in crafting the coding, it was essential for one code not to influence another code. For example, a youth could have current flow (drawing a loop connecting the parts with no redundant lines or shorts) without the drawing being a working circuit (if the parts are not connected in the proper terminal order). Similarly, there could be successful polarity (meaning the terminal orders are correct) while the connections (the connection to the conductive sewing holes in the LilyPad parts) could be lacking. The final categories were primarily whether the participants were able to create a working circuit (i.e., a circuit that would light up the LED), with additional attention paid to:

- Current flow (i.e., making a loop with no redundant lines or instances of shorts.)
- Connections (i.e., craft of the circuit. Lines successfully connect one component to another, and attention was paid to the particular points of conductivity.)
- Polarity (i.e., there is one line between the battery and LED in correct terminal direction: meaning + to + and − to −.)

Each category was scored with a 0 if incorrect or 1 point if correct. Each pre- and post-test had a possibility of scoring 4 points (see Table 2).

The tests were coded by a primary coder on the 1-point coding system. Inter-rater reliability on both the pre- and post-test was established through having a secondary person score over 30 % of the data. Inter-rater reliability was 97 % between the two coders. We then used paired sample *t* tests to determine whether or not the change from pre- to post- test was significant for each of the three coding categories and the larger holistic evaluations of whether or not the youth created working circuits.

Analyzing the Videotaped Observations

The 42+ h of videotaped observations were first logged according to the focus (who) and the current workshop activity. In order for us to fully understand the pre- and post-test findings, the observations were categorized further for learning moments—teaching moments that included the Club member, the mentor/peer, and whether the dialog pertained to current flow, connections or polarity. The current flow, connections and polarity moments were then transcribed and compared to the pre- and post-test results. Youths' design journals were used to supplement videotaped observations, which enabled us to view what the youth were drawing when discussions took place.

Table 2 Pre- and post-test results of circuit diagram assessment using paired samples *t* tests

Circuit diagram assessment	Mean	*N*	SD	Significance 2-tailed
Working circuit pre-test	0.11	17	0.32	.000*
Working circuit post-test	0.78	17	0.43	
Current flow pre-test	0.46	17	0.35	.004*
Current flow post-test	0.83	17	0.30	
Connections pre-test	0.24	17	0.32	.033*
Connections post-test	0.47	17	0.50	
Polarity pre-test	0.17	17	0.29	.000*
Polarity post-test	0.69	17	0.30	

* Significant differences at the $p < .05$ level

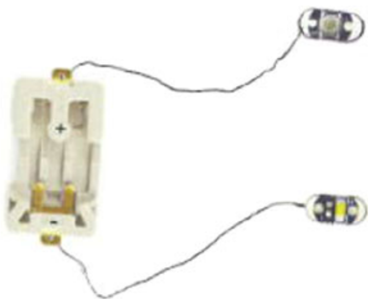
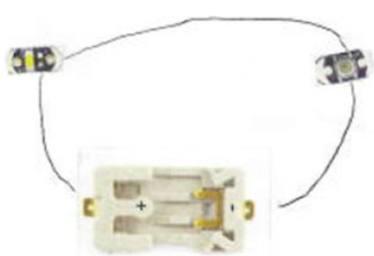
Findings

We first present the results of the pre- and post-circuit diagram assessments, in which we searched for gains in youths' ability to create a working circuit, as well as what the diagrams revealed about our core concepts of interest: current flow, connections and polarity. We illustrate the conceptual shifts toward greater numbers of working circuit diagrams between assessments with three illustrative examples. We then explore each of the core circuitry concepts—current flow, connections and polarity—both through the quantitative results, as well as how the materials cultivated conversation between peers and instructors that supported learning.

Results of Circuit Diagram Assessments

We first sought to understand whether the group as a whole significantly improved in their ability to draw a working circuit diagram from the start to the end of the study. A paired samples *t* test showed that the participants' ability to diagram a working circuit was significantly higher in the post-assessment ($M = 0.78$, $SD = 0.43$) than in the pre-assessment ($M = 0.11$, $SD = 0.32$), $t\ (16) = 4.76$, $p < .001$ (two-tailed). Furthermore, we followed up these findings using additional paired samples *t* tests to examine whether youth increased their understandings of current flow, connections and polarity in addition to their abilities to draw accurate circuit diagrams. A paired samples *t* test showed that the participants' understanding of current flow was significantly higher in the post-assessment ($M = 0.83$, $SD = 0.30$) than in the pre-assessment ($M = 0.46$, $SD = 0.35$), $t\ (16) = 3.34$, $p < .005$ (two-tailed). Similarly, a paired samples *t* test showed that the participants' understanding of connections was significantly higher in the post-assessment ($M = 0.47$, $SD = 0.50$) than in the pre-assessment ($M = 0.24$, $SD = 0.32$), $t\ (16) = 2.31$, $p < .04$ (two-tailed). Furthermore, a paired samples *t* test showed that the participants' understanding of polarity was significantly higher in the post-assessment ($M = 0.69$, $SD = 0.30$) than in the pre-assessment ($M = 0.17$, $SD = 0.29$), $t\ (16) = 4.74$, $p < .001$ (two-tailed). In sum, participants demonstrated a significant gain in their ability to not only diagram a working circuit, but also gained

Table 3 Three illustrative cases: pre- and post-test results

Gavin pre-test	Gavin post-test
	
Gavin lacked the understanding of current flow (circuit path) and the importance of connections of conductive thread	Gavin shows an understanding of the connections as well as current flow (circuit path) and the elements needed for a working circuit
Score = 1: *W0* (Cf0, *C*0, *P*1)	Score = 4: *W*1 (Cf1, *C*1, *P*1)
Jackson pre-test	**Jackson post-test**
	
While Jackson was careful about the connections of the thread to the holes, his network of threads would cause multiple shorts	Jackson shows an understanding of the connections as well as current flow (circuit path) and the elements needed for a working circuit
Score = 1: *W*0 (Cf0, *C*1, *P*0)	Score = 4: *W*1 (Cf1, *C*1, *P*1)
Tanesha pre-test	**Tanesha post-test**
	
Tanesha lacked the understanding of the importance of connections of conductive thread to the holes, as well as polarity of the battery to the parts	Tanesha shows an understanding of the connections as well as current flow (circuit path) and the elements needed for a working circuit.
Score = 1: *W*0 (Cf1, *C*0, *P*0)	Score = 4: *W*1 (Cf1, *C*1, *P*1)

Key = each category worth 1 point: working circuit (*W*); current flow (Cf), whether the diagram is a loop; connections (*C*), whether conductive thread is connected to conductive holes; polarity (*P*), whether positive is connected to positive and negative to negative significantly in their understandings of current flow, connections and polarity (see Table 2).

In the following, we present three illustrative cases that display the type of understanding of the materials and concepts at the start and end of the workshop to elucidate the pre- and post-test results. The three participants, Gavin (age 10), Jackson (7) and Tanesha (10), were chosen as exemplars of the range in types of conceptual gains demonstrated in their working circuit diagrams from pre- to post-assessment. These variations can be seen across the illustrations in Table 3, which display sample pre- and post-assessments for each of these youth.

In the pre-test, Gavin appeared to understand polarity, yet lacked the understanding of current flow (circuit path) and the importance of connections of conductive thread to the conductive holes. While Jackson's pre-test showed an awareness of the importance of the connections issue of the thread needing to connect to the conductive holes, his concept of current flow or the circuit path was quite puzzling in the network-like circuit design, and thus, his polarity was lacking. Lastly, Tanesha's pre-test illustrated an understanding of the overall structure of a circuit loop, though she lacked the understanding of the importance of conductive thread connections to the conductive holes, as well as polarity of the battery to the parts. Still, all three youth were seemingly able to overcome their circuit misconceptions in less than 20 h and come to an understanding of how to create a working circuit diagram.

Qualitative Findings: Learning About Circuits with E-textile Materials

To further unpack how participants gained in their conceptual understanding as demonstrated by their ability to draw functioning circuit diagrams over the course of the workshop, we turned to our videotaped observations and design journal entries to examine instances where youth learned about current flow, connections and polarity through their collaborative experimentations with the e-textile materials.

Learning About Current Flow

Understanding current flow means that youth understand that the energy from the battery needs to be returned to the battery in a loop-like structure. While the loop can take on myriad shapes, the circuit needs to be fundamentally circular in formation. Learning about current flow also means learning about obstacles or ways in which current flow can be inhibited or can bypass the other components in the circuit to cause a short by returning all the battery's energy directly to the battery again. In the following vignettes, we illuminate how the e-textile materials present opportune moments for youth to address and correct their conceptual misunderstandings in the course of producing an e-textile project.

Early in the workshop, youth drew their first circuit in their journal. It was a simple oval circuit, like the sample working circuit solution in Table 1, though youth were able to draw a circuit in a variety of shapes as long as it created a closed loop of some form. Upon completion, youth moved from this conceptual understanding to creating a closed circuit on a quilting square using the e-textile materials. Once engaged with the physical materials, however, initial misunderstandings of circuitry in the abstract came to the fore. One such instance was exemplified in a group conversation that occurred at the end of the quilting square activity:

Researcher:	(Walks to other side of room up front.) Do you have a problem you wanted to talk about? What did you run into?
Katie:	I forgot to cut the thread three times
Researcher:	So you forgot to tie off the thread when you started on the other side of your part, like your light or battery or whatever?
Researcher:	That's really important, too, because if you sew a continuous thread then it won't work will it?
Tyler:	And you will get a short

Katie alluded to one of the easiest ways to make an electrical short, which is to sew all of the electronic parts together in one large circle without terminating the thread as it meets each component in the circuit. Her admission of failing to cut the thread three times referred to the forgetting to tie the thread off at each component and thus the single circuit routed back, without interruption, to the battery, causing it to short. This demonstrates Katie's lack of a deep understanding of what the conductive thread is doing in the circuit (i.e., it is not just a limitation of the tool that the thread needs to stop at each component, but it is essential that the line stops at each component so that the electricity can pass *through* the load). Other kits rarely allow for a mistake like this to occur because forming a closed loop is often an act of assembly—fastening or snapping alligator clips between one or more components. With most traditional toolkits, whether the energy routes *around* or *through* all the components in the circuit is never explicitly addressed, as the tools themselves purposefully limit the kinds of mistakes you can make. Additionally, the number of materials and terminals in an introductory kit is typically constrained. E-textile materials, however, are much more open-ended—Katie, in this example, built an erroneous assumption about how energy flows into her circuit design, and the result was a non-functioning circuit. Had Katie connected her circuit components using alligator clips; for example, she could have reached a working solution without challenging her misconception of current flow. By the LED not lighting up, the tools themselves provided the immediate feedback as to the success of the circuit design.

There are other ways to interrupt current flow. Because conductive thread is not insulated in an e-textile project, it forces the learner to engage in the craft of the circuit. For example, with traditional materials, the arrangement of the wiring is of little importance if the connections between components are correct and intact—wires can cross, bunch and tangle without affecting the circuit's performance and potentially contributes to misconceptions about the circuit's need to be a closed loop. Uninsulated conductive thread, however, makes what happens to the current flow *along the path* more salient, including what can occur if the path changes (e.g., if a piece of loose thread comes in contact with another part of the circuit). Because youth cannot see actual electrons traveling through the circuit, the e-textile materials, by allowing for short circuits, forces the learner to consciously engage in charting the flow of electrons through the circuit. Here is an example between a researcher and Darrion, a 10-year-old male, in which they explore some of the issues encountered with circuit flow with e-textiles:

Researcher:	(Checking over Darrion's project.) Darrion…I want to show you something…See that loop? (Darrion standing, bends over the Researcher and looks.)
Darrion:	Yes
Researcher:	That loop is going to cause you some trouble. Do you know why it's going to cause us trouble?
Darrion:	Why?
Researcher:	You tell me why this is going to cause us trouble
Darrion:	It's touching
Researcher:	It's touching other lines?
Darrion:	Uh huh
Researcher:	Is that a good thing or a bad thing?
Darrion:	A bad thing

Darrion's initial questions back to the researcher indicate that this conversation took place before the mistakes were evident to him. As with many youths' projects, the knotting of the conductive thread was a common reason for a short, especially if the negative and positive lines were close to one another and the knot had a loop (i.e., that could touch the opposite terminal thread line). By contrast, coated wire and alligator clips are designed in such a way as to prevent this issue, thus "protecting" from a number of the learning possibilities that come from observing how shorts and related phenomena come to pass.

Learning About Connections

Making solid connections between components is particularly important in all forms of circuitry, though the concept is made especially salient when using e-textiles. When sewing, poor connections can be manifested as conductive components dangling loosely from the fabric. Youth encountered a range of issues that heightened their awareness about creating solid connections in their projects. In one instance, Joniqua, a 10-year-old girl, tied an insufficiently sized knot to secure a LED to her project, causing the component to fall through the knot when she turned the fabric over. Working with her peers and the instructors, Joniqua soon learned to sew a knot on the underside of the material. While in traditional circuitry, youth can simply use an alligator clip to make connections, e-textiles encourages the youth to think about how to affix the component onto the textile material, so when that material interacts with gravity in various positions, the circuit is still intact and functioning.

Similarly, failing to secure a component by creating several loops around each stitching hole can impact connections, as exemplified in this exchange with Ryan, an 8-year-old male during one of the early sharing sessions:

Researcher:	(Researcher leading discussion with workshop participants). We wanted to talk really briefly about the sewing and what you encountered when you were sewing your circuits. Like, did anybody have a problem…sewing it?
Ryan:	Well, I think I didn't put my, like, needle through the, um, I think the battery or the LED light two times, so it didn't work
Researcher:	Okay. That's very important to put it sew it through two times, right? Everybody?
Youth 2:	Yeah

Ryan recognized the importance of solidly affixing his components with secure knots, creating an opportunity for the group to reflect on the importance of creating solid connections. Both Ryan and Joniqua point to two different ways that youth can learn about the importance of connections in creating electrical circuits, but particularly how its accomplished using e-textile materials.

A lack of connection can also happen along various points in the line. Nail polish, for example, is often used in e-textiles projects to secure knots from untying. However, if too much nail polish is brushed on a line of conductive thread (thus hardening and insulating the thread), the thread's conductivity is impaired. Similarly, if the conductive thread is damaged (e.g., tears in the thread fibers), the connection is also damaged. In this example, Ian, a 12-year-old male, was first trying to unknot a knot with a

Fig. 5 Omarosa's FBI T-shirt circuit design page from her journal, illustrating where the battery placement, LED and switch were to be arranged around the "FBI" design on her T-shirt

needle, while Liam, a 12-year-old male warns him of the conductive effectiveness of the thread if damaged:

Ian: Dude, look at this, look at this, look at this…
Liam: (inaudible) I'm stitching
Ian: I'm going to use my needle to cut the thread. (Methodically pushing the needle through the conductive thread multiple times.)
Liam: (Pulls his needle through the fabric then looks up.) Don't do that, don't do that! Don't, dude, stop! Listen to my explanation why
Ian: (Stops and listens to Liam.)
Liam: Each one of these. You know how it has two threads [double threaded]? Well, a thread.
Ian: (Pulls his thread tight between his two hands and looks at it.)
Liam: That's made of up of, like, five different threads, so that will all fray and that might not be as conductive
Ian: Dude, I have to cut this cause there is a knot there
Liam: Then use the scissors
Ian: (Works on untying the knot.)

This example reveals how one of the youth had garnered enough expertise with the materials, and their connection to underlying circuitry concepts, to share the implications of fraying the line with a peer. The youth in this example brainstorm multiple ways to solve their problem and decide upon a way that would have the least impact on the materials—a key habit of mind to working with electronics, in general.

Learning About Polarity

Unlike traditional light bulbs, current can only flow through an LED in one direction, making LEDs a useful tool to emphasize polarity in a circuit. During the 20 h of the workshop, the one phrase that was used extensively by the staff and the youth was "plus to plus and minus to minus" to help reinforce the importance of polarity in the circuit designs. This phrase indicates that the positive terminal in the battery should connect to the positive terminal in the LED, just as the negative terminal in the battery should connect to the negative terminal of the LED. Though, despite the ubiquity of the mantra throughout the workshop, youth would periodically call on one another for assistance, like in the instance of Adeleke, a 9-year-old female, calling for help from a peer while planning her t-shirt design. Omarosa, an 11-year-old female, had just completed her circuit design for her FBI shirt (see Fig. 5). Adeleke was hoping Omarosa could help her with her design of a Panda T-shirt. Though Adeleke could verbalize what she wanted to happen next in her design, she struggled with creating the corresponding diagram.

Adeleke: Can you please help me?
Omarosa: Well…(Pointing to the page in her journal, sees her partially drawn design.) Put like… draw the battery or something
Adeleke: (Starts to put pencil to her journal.)
Omarosa: But…see what I did? (Shows Adeleke her journal drawing with parts labeled with the positive and negative connections.)
Adeleke: (Stops, looks, then points to Omarosa's drawing.) Battery…
…conversation continues…
Adeleke: (Looks up to Researcher and points at her shirt at the Panda's nose area) Is this [side of the switch] minus or plus?
Researcher: It [the switch] doesn't matter. Where is your light at? (Looks at her t-shirt.)
Adeleke: (Points to the LED sticker on her shirt.)
Researcher: (Pointing to the LED.) The light is what matters
Adeleke: The light is plus to plus (pointing from LED to battery), and minus to minus (pointing from LED to battery)

In this passage, we see that Adeleke was asking for help not because she did not understand how polarity worked, but because she had another component she was seeking to add into the circuit, a switch. Neither youth had a firm enough understanding that a switch does not have polarity; it is simply a place where the circuit is open. But you can see Adeleke applying her knowledge of battery alignment to all elements of her design, which is the impetus for her seeking help on how to incorporate the switch correctly and creating an opportunity for this misconception to be addressed.

Summary of Findings

The transparency of materials is arguably important to youths' conceptual understanding of how electricity works. The results of this study indicate that, through creating diverse projects with transparent and open-ended tools for designing and building their own electrical circuits, youth significantly gained in their ability to diagram working circuits as well as their understandings of core circuitry concepts (e.g., current flow, connections, polarity) after a 20-h workshop. Additionally, the conceptual gains were further supported through opportunities for youth and project staff to engage in discussions about the e-textile materials.

Discussion/Implications for Further Research

The foundation of our inquiry is an understanding that tools change the way one relates to disciplinary content and that moving to a new set of tools makes visible concepts that otherwise may have been invisible to the learner. Such a shift is evident within our own data, where youths' conceptual understandings of current flow, connections and battery polarity were challenged and revised upon the move from designing circuits using pen and paper to fabricating them using e-textile materials. For example, interactions with the conductive thread made visible the effects of barriers on current flow (e.g., sewing through all the parts, knotting) or connections (e.g., nail polish). In addition, the e-textile parts brought about interesting conversations in the conductivity of broken down thread fibers and the importance of the positioning of switches.

In some ways, the additional challenges posed by the e-textile materials, themselves, are compensated by the deeper relationships to content that can be forged through troubleshooting. In contrast to this is the relative simplicity of more traditional tools for teaching introductory circuitry; though perhaps quicker to prototype with (e.g., insulated wires, simplified design of bulbs vs. LED components, etc.), these toolkits unnecessarily limit the number and variety of mistakes that can be made in circuit construction. This may explain why prior research has repeatedly shown the limitation of these materials for providing deep insights into how connections, polarity and current flow work. By contrast, the use of the LilyPad Arduino toolkit allows for more diverse ways for youth to "short" or "break" their circuit, creating manifold opportunities for discussion and questioning of misconceptions. What results is a deeper conceptual understanding through the mistakes and reasoning to fix those mistakes providing opportunities to fix those lingering conceptual misconceptions.

This constitutes a larger rationale for rethinking educational toolkits to support circuitry and potentially other areas of science education, as well. We argue that the most effective toolkits for educational settings allow learners to make a large number of mistakes and should do less to scaffold the learning process. Underpinning our approach is a fundamental view that learning happens best when toolkits afford a sense of transparency by providing opportunities for concretizing knowledge through tinkering with the materials. This "revaluation of the concrete" (Turkle and Papert 1992) is an epistemological stance toward knowledge—the relationships that learners build with knowledge and pathways that facilitate such knowledge construction.

There are also other reasons to consider the addition of e-textile toolkits in science education. Given the recent emergence of national standards in science education that explicitly task educators to organize and present core content with many different emphases and perspectives in order to develop curricula that appeals to *all* students, "regardless of age, gender, cultural or ethnic background, disabilities, aspirations, or interest and motivation in science" (National Research Council 2012, p. 2), now is an especially apt time to rethink the scope of what tools for scientific inquiry are included in the classroom so as to best support the diverse interests and experiences of youth, especially those in populations that science education in the United States has traditionally failed to engage—namely, women and students of color. E-textiles, as one example of a new domain to support science and engineering practices, has already demonstrated its capacity in the professional realm to invite and sustain participation from women (Buechley and Hill 2010). Thus, the emergence of e-textiles as a magnet for creative engineering from traditionally underrepresented groups represents the impact that a richer range of materials in early science education can have on the demographics and perspectives of the next generation of STEM professionals.

While this study focused on simple working circuits and three concept cores, future research studies could include adding directional flow to the current flow model, as well as more advanced constructions to teach series and parallel circuitry. In addition, computational textiles or the full line of the LilyPad Arduino Toolkit, including the microcontroller, sensors and actuators could be explored, adding levels of complexity which is more in line with and comparable to the current robotics model.

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