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DEVELOPMENT ARTICLE

Learning design for short-duration e-textile workshops: outcomes on knowledge and skills

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Abstract

E-textiles provide an interesting field of research as they "blend traditional craft with modern science" (Peppler, 2016) and help learners "broaden their own perceptions of computing" (Searle et al., 2016). Despite the promising findings by primarily long-term interventions structured around e-textiles, educational curriculum reform has been slow to materialize. Educators who embrace a STEAM philosophy are more likely to endorse short workshops, integrating them in existing courses or initiatives; this could serve as a steppingstone for longer interventions and bottom-up curriculum reform. This study examines whether shorter e-textile workshops (lasting four hours) can result in significant gains in understanding. We present an investigation of e-textiles with 22 young children who have no prior experience with e-textiles or working with microprocessors. We present details of our learning design, as well as findings related to circuitry knowledge and computational making skills. We find that the children advanced their circuitry knowledge and practice a range of computational making skills. We further document a series of emerging challenges, including the children's unwillingness to engage or lack of adeptness with software, a tension between aesthetics and construction, creativity limited by samples of previous e-textile projects, and the difficulty in grasping the materiality of e-textiles. We propose that some direct instruction and facilitation is not incompatible with the making ethos; the approach can help address these challenges, allowing young children to benefit from their participation in short-duration e-textile workshops.

Keywords E-textile workshops · Computational making · BBC micro:bit · STEAM · Learning design

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Introduction

The last few decades have witnessed a growing interest in the maker movement due to its potential to transform STEAM (Science, Technology, Engineering, Arts and Mathematics) education (Ioannou & Gravel, 2024; Patton & Knochel, 2017). The maker movement encompasses an active process of designing, building, and innovating with tools and materials to produce shareable artifacts through all types of making, such as cooking, sewing, embroidery, weaving, welding, woodworking, robotics, soldering, printing, painting, and building (Martin, 2015; Peppler & Bender, 2013). One of the cornerstones of the maker movement is interaction with physical materials through the utilization of affordable and widely accessible digital tools and technologies (Martin, 2015; Timotheou & Ioannou, 2021a, 2021b). The experience extends to accommodate "beyond desktop" computing, otherwise known as computational making (Rode et al., 2015; Litts et al., 2021). Transitioning off the desktop has been facilitated by the miniaturization of computing and the increased simplicity of programming microprocessors and computational tools. This development has opened new educational pathways, in other words, it has allowed making activities to play a prominent role in the transformation of formal and non-formal education settings, such as school or non-school spaces, makerspaces, or maker camps (Rode et al., 2024a; Papavlasopoulou et al., 2017; Peppler & Bender, 2013).

More recently, the research community has turned its focus to computational making practices with the use of electronically enhanced textile projects—e-textiles (Fields et al., 2019; Litts et al., 2021; Rode et al., 2015; Rode et al., 2024b). E-textiles provide an interesting field of research as they "blend traditional craft with modern science" (Peppler, 2016) and help learners "broaden their own perceptions of computing" (Searle et al., 2016). E-textile kits have evolved to now include a range of electronic tools, such as microcontrollers, sensors, switches, power supplies, and actuators, which are manipulated via coding applications and craft tools, such as conductive thread and needles (Searle et al.,; 2019; Fields et al., 2017). They are often used as a vehicle for STEAM teaching, as the powerful combination of crafts, coding, and circuitry can motivate learners' scientific explorations in conjunction with their creative making and programming activities (Peppler, 2016; Rode et al., 2024).

To date, studies have primarily focused on examining the impact of e-textiles in school settings in relation to the science curriculum, primarily using long-term interventions (Fields et al., 2019; Hébert & Jenson, 2020; Searle et al., 2019). Despite the promising findings, educational curriculum reform has been slow to materialize. Peppler (2016) has also emphasized the importance of investigating whether "significant gains in understanding can be made in a much smaller timescale" (p. 279). Indeed, very few research efforts have focused on introducing e-textiles to young learners in the context of short workshops (e.g., see some of the workshops in Litts et al., 2021). Yet, educators who embrace a STEAM philosophy are more likely to endorse e-textile workshops of shorter duration, integrating them in current courses or initiatives; this approach could serve as a steppingstone for longer interventions, fostering a bottom-up approach to curriculum reform. Nonetheless, in order to implement short workshops that enable learning outcomes, novice educators and tutors need workshop models and examples that explain how to handle the variety of tools and materials required in e-textiles (Peppler, 2016). They also need a learning design i.e., the processes of facilitation for learning that put emphasis on learner participation and responsibility (Wasson & Kirschner, 2020). Building on this idea and considering e-textiles as a compelling platform for STEAM, we present a learning design for a short, introductory e-textile workshop and we document significant gains in children's knowledge and skills. The research questions are the following:

RQ1: What is the impact of a short e-textile workshop on students' understanding of coded circuitry?

RQ2: What is the impact of a short e-textile workshop on students' practicing of computational making skills?

Background

Building on applications of constructionism, the maker movement has opened up new possibilities of interaction with physical materials and new opportunities for learning in STEM and STEAM (Gravel et al., 2022; Honey, 2013; Ioannou & Gravel, 2024; Martinez & Stager, 2013; Timotheou & Ioannou, 2021a) via open exploration, intrinsic interest, and creative ideas (Peppler & Bender, 2013; Timotheou & Ioannou, 2021b). Making practices can be implemented through affordable and accessible off-the-desktop technologies which are associated to physical computing (Rode et al., 2015; Litts et al., 2021; Peppler, 2016).

E-textiles, computational making, and creativity

E-textiles have come to the fore as an ideal tool to introduce STEAM to young learners (Peppler & Glosson, 2013). Engaging with an e-textile project can nurture creative design and building skills as it combines elements of engineering, crafting, and programming (Kafai et al., 2014; Litts et al., 2017; Searle et al., 2016). E-textiles are essentially textiles or fabrics with embedded digital and electronic functionalities (Posch & Fitzpatrick, 2018). E-textile kits include programmable microcontrollers used for processing input and output from a variety of devices (Martin, 2015). The ultimate goal is to connect the electronic components with textiles by creating knitting patterns on the textile material based on its properties (softness, flexibility, and aesthetics), which enables new uses and interaction scenarios (Peppler, 2016; Posch & Fitzpatrick, 2018). Litts et al., (2017) refer to e-textiles as circuits constructed with conductive thread, sewable LEDs, sensors, and microcontrollers. The codable circuits in these electronic components have functionality that can be designed and controlled via programming. Litts et al., (2017) also state that "learning how to make codeable circuits sits at this very intersection and involves students in designing and crafting a functional circuit that also can be controlled via code" (p. 494). Overall, e-textiles are a powerful tool in STEAM and maker education, especially due to their potential in supporting the conceptualization of circuitry, a topic that students often find challenging (Peppler, 2016).

The use of computational making methods incsorporating e-textiles has recently attracted increasing interest (Rode et al., 2024). Engaging in e-textile projects can aid in the creative design and construction of tangible objects by bridging the domains of engineering, craftsmanship, and programming (Kafai & Peppler, 2014; Kafai et al., 2014). Halverson and Sheridan (2014) emphasized that e-textiles serve as an innovative medium to introduce computational concepts to children in a tangible and visually appealing manner. As they discuss, the fusion of technology with textiles opens new avenues for creative expression and problem-solving, as children actively engage in designing artifacts that respond to their inputs and interactions. Kafai et al. (2014) supports this notion too, highlighting how e-textiles enable children to become designers and creators of their interactive projects, and therefore, bridging the gap between technology and creative artistry. Rode et al. (2015) highlight that computational making needs further investigation to develop effective educational practices. They describe five key challenges that children face in their computational making activities: (1) aesthetics, (2) creativity, (3) constructing, (4) visualizing multiple representations, and (5) understanding materials. Per this framework, the child is the artifact creator who makes autonomous judgments and applies nonlinear processes when constructing artifacts; *Aesthetics* is the way children strive to make technologies aesthetically pleasing; *Creativity* is a problem-solving skill that allows for playful flexibility; *Constructing* refers to the physical skills required to make artifacts; *Visualizing multiple representations* is the child's ability to connect two-dimensional (2D) representations to three-dimensional (3D) artifacts; and *understanding materials* is the ability to map functionality and outputs onto different materials (Rode et al., 2015).

Understanding of coded circuitry in e-textiles

Most studies have examined the impact of e-textile making activities in formal education settings in relation to the science curriculum (Hébert & Jenson, 2020; Jayathirtha, & Kafai, 2019; Searle et al., 2019) and, more specifically, the topic of circuitry (e.g., Halverson et al., 2016). An ever-increasing corpus of research highlights that students tend to struggle with circuitry concepts. Topics like polarity, current flow, and circuit connections, are some of the main weaknesses related to students' understanding of circuitry. In short, research has shown that young students experience difficulties in the conceptualization and drawing of circuitry (e.g., Shepardson & Moje, 1994). According to Peppler (2016), this lack of understanding is perpetuated by the tools and materials used in traditional learning experiences (e.g., light bulbs, light sockets, some types of batteries), as these render the structure and functionality of circuitry highly opaque. A call for different mechanisms to promote students' understanding of circuitry has thus emerged, highlighting the need for more compelling and transparent learning approaches (Kafai, & Peppler, 2014). In this context, e-textiles have been suggested as a vehicle for introducing circuitry to young learners. E-textiles can provide a more transparent visualization of circuitries. For example, "the uninsulated threads allow for shorts that are oftentimes prevented with our typical electronics toolkits, where we might snap circuits together with alligator clips or other similar devices" (Peppler, 2016, p. 278). When talking about "coded" circuitry, Blikstein et al. (2017) have pointed out that empirical studies should focus both on the evaluation of students' understanding about circuitry as well as of students' understanding about coding and programming (see also, Keune, 2022; Fields et al., 2016).

Overall, a growing corpus of studies has provided empirical evidence supporting the promise of e-textiles in STEM, STEAM, and maker education (e.g., Kafai et al., 2014; Peppler & Glosson, 2013; Tofel-Grehl et al., 2017). These studies typically present extended interventions, despite calls to also investigate whether "significant gains in understanding can be made in a much smaller timescale" (Peppler, 2016, p. 279). Considering that schools do not necessarily offer a flexible environment in which educators and practitioners can implement long-term interventions, the extent to which shorter workshops may produce similar results is a worthy avenue for research. Peppler (2016) goes on to elaborate that novice educators and tutors need new guiding pedagogies and workshop models to deal with the variety of tools and materials required in e-textiles. Despite e-textiles being a compelling platform for STEAM education, there is still a gap in the literature regarding detailed learning designs for short introductory workshops that effectively foster the development of relevant knowledge and skills.

Methodology

The presented study used both quantitative and qualitative data collection and analytical techniques to address the RQs. Data were collected from young children taking part in a four-hour workshop introducing them to e-textiles.

Participants

Twenty-two ($n = 22$) students volunteered to participate in the workshop, which took place as a summer school activity, hosted at a public makerspace in Cyprus. There was an even split of boys ($n = 11$) and girls ($n = 11$), and a mean age of 12.7 years (SD = 1.26). The participating students were recruited through an open call disseminated to various educational groups, leveraging the affordances of social media. Before the intervention, consent forms were obtained from the students' legal guardians, while opt-in assent forms were obtained by the participating students. During the workshop, the participating students worked primarily in self-selected, same-gender pairs. Most students who paired up knew each other prior to the study and had signed up to participate together. None of the children had previous experience with e-textiles or working with microprocessors (we believe that this was the first time that such a workshop was done in Cyprus). Table 1 presents the participating students' age, gender, and project per pair.

Procedures and data collection

The workshop covered electronic components, circuitry, and basic programming, allowing it to be easily integrated into existing STEAM-oriented courses. For their projects, the children worked in pairs to create a small stuffed object of their preference equipped with

Table 1 Participating students' age, gender, and project

ID	Gender	Age	Project	ID	Gender	Age	Project
1	M	12	Yellow star	13	F	15	Yellow owl
2	M	12		14	F	13	
3	F	12	Globe	15	M	13	Audi logo
4	F	16		16	M	13	
5	F	12	Pink/black cat	17	M	13	Orange tiger
6	F	11		18	M	12	
7	M	15	Yellow man	19	M	12	Black TV with camera
8	M	12		20	M	12	
9	F	11	Red heart	21	M	12	Orange cat
10	F	12		22	F	12	
11	F	13	Pineapple				
12	F	14					

Table 2 Data collection

Knowledge exercise (individual data, pre-test/post-test) i.e., asking the children to draw two circuits, one with a battery and a lamp, and another with one battery and two lamps
Circuit diagram (group data, pre-test/post-test) i.e., pictures of the circuit diagrams with no facilitator input at post-test
Programs/code (group data, post-test) i.e., screenshots of all participants' project code on the computer screen
E-textile artifacts (group data, during the experience) i.e., pictures of the in-development (i.e., a picture about every hour) and final projects/artifacts
Fieldnotes i.e., facilitators' notes based on close observation of the pairs (three per facilitator) collected during the experience
Video analysis i.e., recordings for each group during the experience, to allow further analysis and overall triangulation

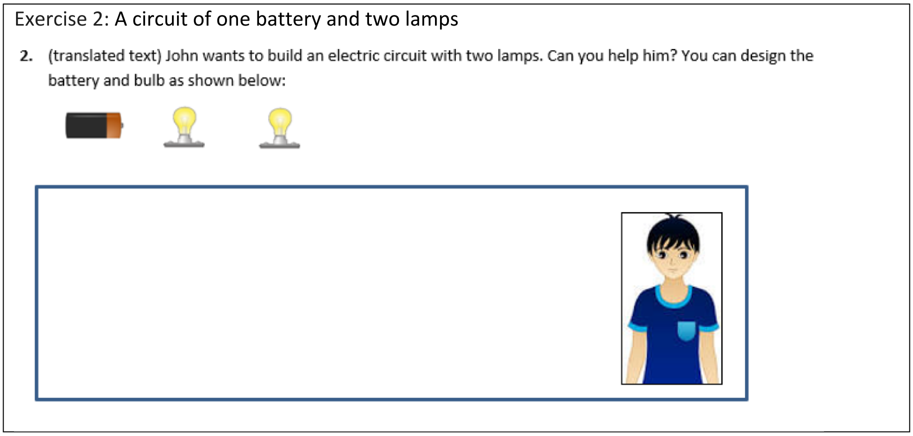


Fig. 1 Knowledge exercise

circuitry, including LEDs and a microprocessor. They were tasked to program the object to light up in response to button presses.

The four-hour workshop was conducted in two sessions (two hours each), with a 30-min break between the sessions. The children all spoke English, the language used in the workshop. Four researchers acted as facilitators and were present throughout the workshop to help the children with their projects. Each facilitator was responsible for three pairs. For a microprocessor, the BBC micro:bit was selected due to its accessible. Also at the time, BBC micro:bits were easily available and a low-cost option (compared to similar hardware such as LilyPad Arduino).

Session 1: Preparation and hands-on practice (2 h)

A five-minute knowledge exercise was administered first, in which the children were tasked to draw two circuits, one with a battery and a lamp, and another with a battery and two lamps (see Table 2 and Fig. 1). This type of test has been used effectively in previous studies (e.g., Litts et al., 2017; Shepardson & Moje, 1994).

Next, the participants received a hands-on introduction to e-textiles, including how to create a simple circuit, how to work with conductive thread and sewable alligator clips, and how to use and program the micro:bit. We demonstrated the micro:bit basics, after which the children practiced different actions e.g., how to get a button press to trigger an action (on Button command), how to scroll their name across the micro:bit screen, how to program their micro:bit so that it acts like a light sensor, and how to turn their micro:bit into a step counter.

Moving on from the basics, we did the same with explaining, demonstrating, then asking the children to take turns with simple circuits using LEDs and alligator clips. For example, the alligator clip was connected to one of the signal pins (fingers, labelled 0, 1, and 2), and then to the positive terminal of the LED. We worked with how to map zero to off, how to map one to one for the LEDs, and how to turn a LED on and off (Digital-Write command).

Next, we covered the Ohm's Law, which is featured in the school science curriculum (ages 11–12). Ohm's Law tells us that the current is directly proportional to the voltage and inversely proportional to the resistance, mathematically expressed as $V = I/R$, where V is voltage, I is current, and R is resistance. Through practical activities, the children understood that adding more LEDs required more current and thus more batteries. We also explained that resistance could be reduced by using two strands of thread when sewing i.e., threading a needle, and using a knot to tie both pieces together, as opposed to the traditional way of sewing where only one piece is knotted.

Last, we explained that both series and parallel circuits are valid ways to connect multiple LEDs to the micro:bit, and that connecting them individually also allows for independent control. The children could elect to connect the LEDs in series or in parallel (i.e., all LEDs controlled together) or aim for individual control so that each LED could be programmed independently (see Fig. 2). We prompted the children to consider this important design decision in planning their projects, as it would strongly influence what they could program their project to do.

Session 2: Project development phase (2 h)

The children had to think of an e-textile project with some degree of interactivity i.e., controlling between one and three LEDs. They saw sample e-textile projects with LEDs that looked like the FIFA logo, a purple cat with light-up eyes, a shooting star, a heart logo of a popular company with eyes, and a rocket ship with flames that lit up.

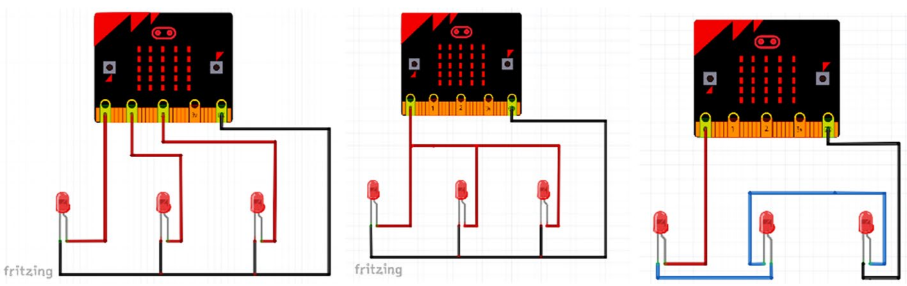


Fig. 2 (L to R) Individual LED control; all LEDs controlled together in parallel; and all LEDs controlled together in a series

First, the children drew the circuit diagram of their planned project on A4 paper, making sure that the micro:bit would fit. They labeled the positive and negative polarity of batteries, and marked the current flow, focusing on possible missing connections. This intermediate step was crucial, as it enabled children to discuss their designs within their pairs, consider the circuitry before implementation, and solve potential problems amongst themselves. We avoided providing answers or correcting their circuits; when needed, we scaffolded their thinking towards creating functioning circuits before moving on to crafting. We took pictures of the initial diagrams (i.e., circuit diagrams pre-test).

Second, before moving on with the actual development of their e-textile projects, we reviewed the diagrams to either confirm a valid circuit or provide feedback. Facilitators did not fix the diagrams, but instead asked questions to guide the children to identify potential problems. For instance, if the pair had a crossed trace in the circuit, we would encourage them to track the path of the electricity starting at the positive terminal of the battery through the circuit and reflect. This resulted in them drawing a valid circuit before proceeding to the next step—creating their e-textiles artifacts.

The third step was for children to sew the circuit, test and debug it, and finish by adding decorative elements to their e-textile project. Materials provided included sewable LEDs, sewable alligator clips, felt and fabrics, conductive thread, needles, scissors, and fabric glue. Before submitting their projects, we asked the participants to revisit their circuit diagrams and make any adjustments they saw fit. As facilitators, we completely refrained from providing input on their post-test diagrams. We took pictures of the final diagrams (i.e., circuit diagrams post-test) and screenshots of their code on the computer. We also took pictures of their in-development and submitted e-textile projects. Note, the participants all wanted to take their creations home, which the facilitators allowed. We also administered a five-minute knowledge post-test. Table 2 summarizes the resulting data.

Findings

Students' understanding of coded circuitry (RQ1)

Circuitry exercises (individual data)

The exercises were scored according to a rubric developed by Peppler and Glosson (2013). We evaluated students' performance in relation to the following simple circuit aspects: connection, polarity, and current flow. More specifically, as in the study of Litts et al., (2017), (a) we evaluated the connection types (as either loop or linear connections); (b) we identified the matching polarity between the battery and the light; and finally, (c) we evaluated current flow by focusing on missing connections, redundant lines, and crossed lines/short circuits. We coded and evaluated each specific feature as 1 (present) or 0 (not present). In addition, we coded and evaluated with 1 if the drawn circuits were functional. Due to the small sample size and the dichotomous coding, we conducted McNemar's tests to measure the changes in students' understanding for each of the aforementioned circuitry features.

Our findings showed that students' ability to create accurate representations of a simple circuit significantly increased ($p = .016$) from pre- to post-test (see for example, Fig. 3). Specifically, by the end of the e-textile workshop, 19 students (86%) were able to draw a functional circuit, up from 12 (55%), prior to the workshop.

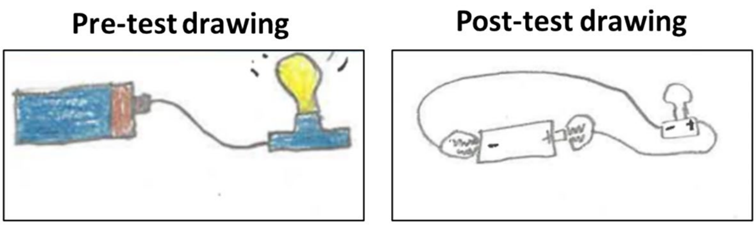


Fig. 3 Example of a non-functional circuit (pre-test) on the left, versus a functional circuit on the right (post-test)

Still following Litts et al., (2017), we also investigated the impact of the workshop on students' ability to draw a simple circuit (Table 3). There was a significant improvement of students' understanding of matching polarity ($p = .039$) and a significant reduction in their mistakes in relation to missing connections ($p = .031$). Last, we found an improvement, albeit not statistically significant, of students' understanding of the remaining features of a simple circuit.

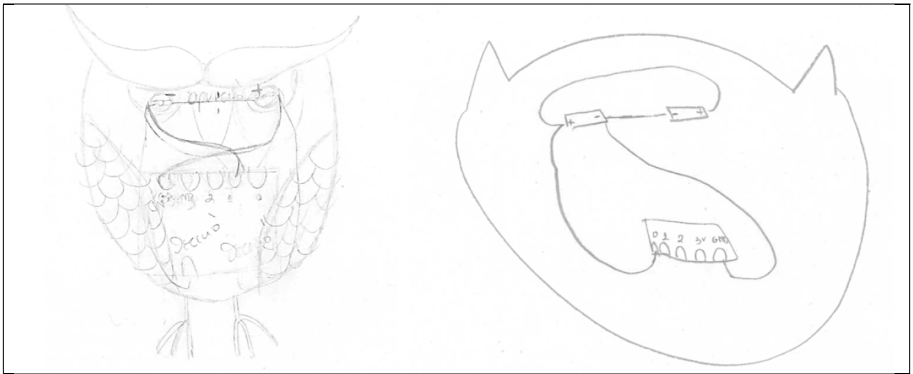
E-textile circuit diagrams (group data)

The projects' circuit diagrams were then evaluated for improvements (see an example of evaluation in Fig. 4). The participants (11 pairs) had no input from their facilitator as they designed post-test diagrams. The overall results showed that: three pairs improved their circuit design, from an incorrect drawing at pre-test to a correct one at post; one pair designed a flawed circuit in the post-test (conductive thread crossing, therefore making the circuit non-functional); and seven pairs drew a correct circuit both before and after. Three of these seven pairs benefited from the facilitators' scaffolding before the test. In sum, the positive findings from the evaluation of the circuitry exercises were triangulated in the analysis of pre-/post-test diagrams. A sample of circuit diagrams are presented in Fig. 5.

Table 3 Understanding of circuit features (pre- and post-test)

Circuit feature	Pre-test ($n = 22$)	Post-test ($n = 22$)	Significance
Polarity (matched)	1	8	.039*
Connection type (loop)	19	21	.500
Current flow: Missing connections	10	4	.031*
Current flow: Redundant connections	2	0	.500
Current flow: Crossing lines/Short circuits	3	0	.250
Circuit functionality	12	19	.016*

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



Pre-test: The pair did not manage to draw a functional circuit: Circuit is not represented as a loop. Crossing lines prevent proper functionality of the circuit. Polarities between the lights and the BBC micro:bit do not match. More emphasis on the aesthetics of the owl, rather than a functional circuit.	The pair managed to draw a functionable circuit. Circuit is represented as a loop. No crossing lines prevent proper functionality of the circuit. Polarities between the lights and the BBC micro:bit match correctly. More emphasis is given on the functional circuit rather than on the aesthetics of the owl.

Fig. 4 Example of evaluation of circuit diagrams pre-to-post, “Yellow owl” (13F & 14F)

Students' practicing of computational making skills (RQ2)

Code evaluation (group data)

Frist, the children's code (group data) was analyzed for correctness and complexity. Evaluating the 22 participants' code was made simple using micro:bit's MakeCode editor (Scratch-style). For the most part, the final code closely resembled the sample code demonstrated in Session 1 (see Fig. 6). All the participants' code used the Digital-Write command to control the LEDs primarily in response to the press of a button. Almost all pairs programmed the LEDs to turn on in response to “Button A” and off in response to “Button B” like in the examples given. The makers of the "Orange tiger” project (19 M and 20 M) were the only ones to add extra code (to display their name on the simultaneous press of buttons A and B). Although, we had practiced the “Forever” loop, which makes the micro:bit scroll their name, none of the children elected to put code in it, despite this loop existing as a default in the MakeCode editor. The makers of the Audi logo (17 M and 18 M) programmed their project to turn off as it booted up, showing a failure of applying coding skills. In general, the study did not document any advancement in children's coding skills.

E-textile artifact evaluation (group data)

We then analyzed our findings to gain an understanding of how children handled the electronics, coding, and constructing of e-textiles. The computational making framework

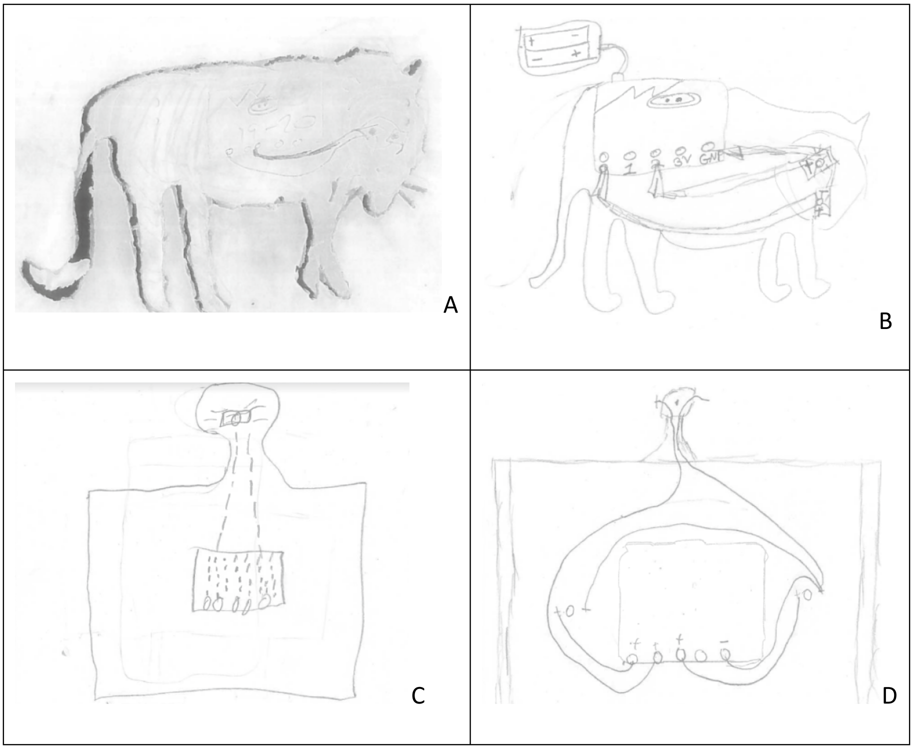


Fig. 5 A and B represent the pre- and post-study circuit diagrams for "Orange tiger" (19 M & 20 M). C and D represent the pre- and post-study circuit diagrams for "Black TV with camera" (21 M & 22 M). Note that both pre-test diagrams show lack of understanding of circuitry

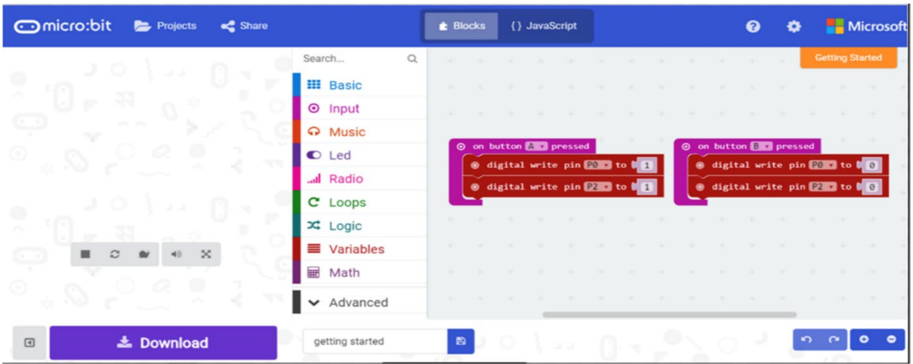


Fig. 6 Code from participants who created the "Yellow star" project

(Rode et al., 2015) was our analytical lens for coding the qualitative facilitators' fieldnotes, then triangulating with e-textile projects/artifacts and video data. We started with the facilitators' fieldnotes, classifying the corpus per the main dimensions of the framework: aesthetics, creativity, construction, visualizing multiple representations, and understanding materials. The coding of the fieldnotes from all four facilitators was initially done by one researcher (last author). A second researcher (first author) also did the coding independently. There was nearly at 90% agreement between the coders and all disagreements were resolved after discussion, therefore reaching consensus. Triangulation of the findings was achieved by juxtaposing the coded fieldnotes to the final e-textile projects/artifacts. Finally, the video recordings (one video per group) were examined around pivotal moments triggered by the facilitator's fieldnotes. Although we did not interview the children about their decisions, they did talk about their choices with their peers (captured in the video) and these conversations amongst children allow us to present multiple readings of their motivations. The synthesis of these data resources allowed for a portfolio to be documented for each of the e-textile projects and pairs of children.

Samples of the children's projects appear in Fig. 7, while the full list of project names can be found in Table 1. In sum, all 11 pairs were able to create a working circuit with help. Three pairs—those working on "Globe" (3 and 4F), "Pink cat" (5 and 6F), and "Yellow man" (9 and 10 M) required substantial assistance. Based on the beginner learning session, the e-textile projects stimulated a range of skills found in the computational making framework. At the same time, we also documented diverse challenges related to computational making, particularly in artifact construction. Below, we present findings categorized under the five dimensions of the computational making framework.

Aesthetics

After seeing the sample projects, most participants immediately envisioned what they wanted to make. Most used the LEDs either as eyes for animals, or as decorative elements for objects such as a heart, a pineapple, and a football cup. Once they had settled on their artifact, the children had to choose the number and placement of the LEDs. The pair with a heart opted for just one LED centered on the left side of the heart, whereas others used up to three ("Globe," "Football cup," and "Black TV with Camera"). Most children used

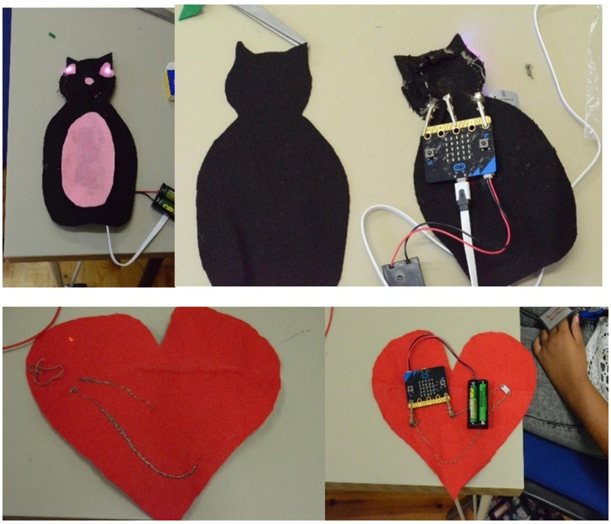


Fig. 7 Cat project front and inside using two LEDs as eyes (top). Heart project front and back using one LED. Note stray thread (bottom)

two LEDs (average 2.09). This may suggest that aesthetics were secondary to technical function (we will revisit this argument in the creativity section, below). It is worth noting that there was a variation in children's projects in terms of aesthetics. For example, we had three versions of a cat. One was black with a pink belly and light-up hearts for eyes. Another was a realistic side view of an orange tiger. Finally, we had a front view of a stylized orange house cat with a large fluffy tail. While conceptually similar to the cat presented as a sample, each pair presented their own aesthetic vision. All the participants chose to take their artifacts with them, which suggests they were happy with their creations. We did not observe any debates about which participant of the pair got to keep the artifact, perhaps because in most pairs, the participants were friends and joined the workshop together.

Creativity

Although we showed the children sample projects (e.g., a FIFA logo, a purple cat with light-up eyes) and practiced with sample code in Session 1, we challenged the children to be creative and use their own ideas for a project. We note the similarity of the sample projects and theirs. We had one FIFA logo (25 and 26 M), three cats (5 and 6F, 19 and 20 M, and 23 and 24 M), and a heart (11 and 12F). While we cannot know for certain, it is possible that some of the sample designs inspired others; perhaps the shooting star inspired the globe (planet earth), or the heart logo inspired the Audi logo. Some appeared to be entirely original such as "Pineapple" (13 and 14F), "Yellow man" (5 and 6 M), and "Black TV with camera" (21 and 22 M). Similarly, as discussed above, we saw that the children did not program much beyond our sample code. This suggests that creativity was hampered by a desire to achieve technical mastery, an ever-present tension in STEAM education.

We did see children put effort into selecting their projects. Some browsed online for images as was the case of the designers of the "Red heart" (11 and 12F), and the makers of "Yellow man" (25 and 26 M). Second, individual creativity may have been impacted by the need agree on a shared project as in the case of the creators of "Pink cat." However, we also have evidence of children compromising their creativity in some collaborations. For instance, 9 and 10 M debated whether their "Yellow man" should be green, black or yellow. This discussion prompted them to play rock-paper-scissors, a children's game sometimes used to help make decisions. They end up choosing green. Similarly, 25 and 26 M compromised creative control over the design of the object. Child 26 said to child 25: *"give me the pencil... I am better than you are in this [drawing]."* Later, child 25 asks child 26 if he is *"designing it."* The reply came, *"I don't know what I am doing."* Thus, we see that children who felt their artistic skills were lacking often took the back seat in the planning phase.

Constructing

Like in Rode et al. (2015), we saw problems stemming from children's attempt at manipulating tools, especially using scissors and threading needles. Felt is a difficult material for children to cut, which is exacerbated by the dullness of the scissors they had access to. Figure 8 shows a ragged edge, which did not match the child's sketch of smooth lines and a symmetric face. Similarly, conductive thread is more difficult to work with than regular thread due it being less smooth; this can be mitigated by applying beeswax, although we may not have made this apparent enough to the children. Children struggled to get all

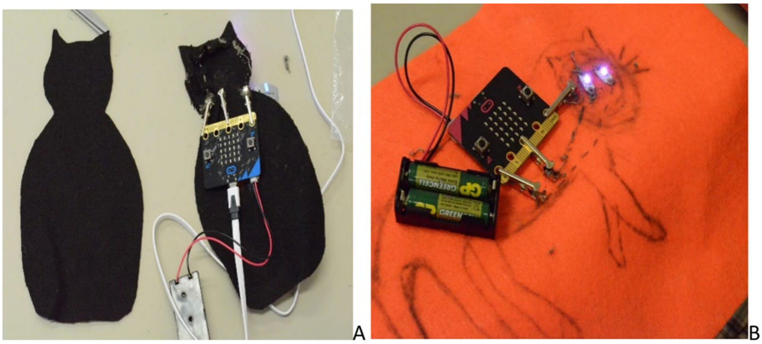


Fig. 8 Close-ups of two projects depicting cats: **A** Pink cat and **B** Orange tiger. For both, note the frayed thread and alligator clip placements

strands of thread through the eye of the needle. See Fig. 8 for example of frayed thread which made fuzzy balls attached to the felt, which caused short circuits, or short circuits making issues with circuits difficult to debug, which can be seen in both A and B. Poor connections and loose knots often made LEDs flicker, something that was difficult for the children to debug. Such issues combined resulted in "Globe" (3 and 4F) and "Pink cat" (5 and 6F) to fail as projects. We worked with these participants to help them discover how removing thread fuzz, and tightening stiches and knots would make their projects work properly.

Visualizing multiple representations

Before moving on with the actual development of their e-textile artifacts, the children were requested to draw a circuit diagram of their planned design on A4 paper. Some of the children perceived this intermediate task as an unpleasant chore, one that posed an unnecessary delay to the development of the artifact itself. However, the facilitators noted that it was a crucial step towards the successful completion of the project as it would allow the children to conceptualize their planned designs in conjunction with the circuitry. The facilitators noticed that this visualization also triggered some interesting discussions between some pairs in relation to the positioning and functionality of the circuits, as well as coding. At the same time, these visualizations provided a window into the children's ideas and misconceptions, which the facilitators used as an opportunity to address. They initiated discussions with the groups around these visualizations—so-called 'teachable moments'—asking them to elaborate further on their ideas, questions, and concerns around their circuitries. Using the circuit diagrams, the facilitators were able to provide feedback at an early stage.

Understanding materials

Another challenge the children encountered was manipulating the materials to achieve their design goals, especially as they did not have a complete understanding of material properties. Some materials, such as felt and regular thread, were familiar, whereas others, such as conductive thread and micro:bits, were new. Consequently, several children tied conductive thread and left inch long tails as one would with traditional handicrafts. In this project, this practice resulted in shorts. These shorts were exacerbated by poor sewing skills and the tendency to create fuzz (Fig. 8). On the other hand, we did see some instances where children mastered material properties, in particular, conductivity. Given the children were struggling with the small hole on the alligator clip, a few wrapped the thread around the body of the clip. They correctly understood that more contact reduced resistance on the circuit (see Fig. 8).

Discussion

We conducted an investigation of e-textiles to understand the *impact of a short introductory e-textile workshop on students' understanding of coded circuitry (RQ 1) and practicing of computational making skills (RQ2)*. Overall, the study suggests that young students can indeed benefit from participating in short e-textile workshops. We have evidence that circuitry knowledge was advanced and that the e-textile projects stimulated a range of skills from the adopted computational making framework. However, we also documented a series of challenges related to computational making. Much of the discussion that follows focuses on these challenges and how future learning designs of such workshops can be adapted to address them.

Gains in circuitry knowledge

Overall, the e-textile workshop had a positive impact on the children's circuitry knowledge. As in previous empirical studies, typically of longer duration, we found that students' ability to draw a functional circuit improved during the workshop (e.g., Halverson et al., 2016; Litts et al., 2017; Peppler & Glosson, 2013). At the same time, we witnessed a significant increase in students' understanding of circuit features, such as matching polarity, as well as a reduction of common errors related to current flow, such as missing connections. These findings provide empirical support for previous research reporting that e-textile making activities structured around microcontrollers can support students' understanding of circuits (Fields et al., 2017; Kafai & Peppler, 2014; Kafai et al., 2014; Rode et al., 2024; Tofel-Grehl et al., 2017). The findings also provide evidence that such outcomes can be achieved via shorter, introductory workshops. We therefore suggest that young children can benefit from participating in short workshops on e-textiles. Such workshops have a high chance of being endorsed by educators who embrace a STEAM philosophy, as they can easily be integrated in ongoing courses or initiatives. They can also serve as a step towards longer interventions and bottom-up curriculum reform. Conducting just one four-hour workshop enabled us to document knowledge gains for our participants. The detailed learning design of our workshop, as presented here, can be used to enable more educators to integrate e-textiles and circuitry in their work and curriculum.

Limited programming ambitions or practice in relation to software

The children showed little ambition to try new things in their programming efforts, which was a barrier to discovering the full potential of their computational thinking. The code they produced overall closely resembled our sample code, which was presented in the preparation session. Only one group added some extra code that had not been provided in the sample code. Another group attempted to program something new, resulting in their project turning off as it booted up, which was counter-productive and showed a failure of applying coding skills. We ultimately have little evidence of gains in coding skills through this four-hour workshop. This can be partially attributed to the learning design choices, which did not emphasize working with coding. This finding relates to previous calls for learning to focus on coding and programming in addition to understanding of circuitry (Blikstein et al., 2017). We thus argue that teaching coding and programming is necessary as a preparatory step, if we want students to practice working with software in e-textile projects. Our findings should by no means be interpreted as a 'weakness' of e-textile projects in supporting students' coding skills. Instead, the lack of evidence of improvement should be attributed to the nature of our workshop, which puts less emphasis on this aspect. Meanwhile, our findings show that although the workshop may have provided space for practicing coding skills most opportunities for practice occurred in relation to hardware not software, and they were complicated by difficulties produced by constructing and understanding materials (see also Rode et al., 2024b). Yet, while not explicitly evident, the open nature of the e-textile projects likely encouraged skills such as formulating problems or automating solutions via algorithmic thinking skills. We would argue that coding and programing skills in the context of e-textiles need to be further investigated by the research community to develop educational practices to teach these skills effectively.

Tensions between aesthetics and constructing

In the majority of the projects, children's aesthetic visions were not fully realized in the final e-textile artifacts. This might suggest that there is a delicate interplay between design and children's technical skills (i.e., coding, debugging incorrect circuits, constructing with materials) that needs to be developed before children engage with e-textile projects. Additionally, the children's ability to implement their design was impacted by their understanding of material properties. Including some preparatory hands-on constructing activities, during which children could be asked to debug and correct incorrect circuits (e.g., see debugging activities introduced by Fields et al., 2016) may decrease the tension between aesthetics and constructing.

Samples of previous e-textile projects limiting creativity

At the outset of the workshop, we thought that sharing several examples of e-textile projects (e.g., the FIFA logo, a purple cat with light-up eyes, a shooting star, a heart logo, and a rocket ship with flames that lit up) would help the children envision the expected outcome. While these ideas seemed to have inspired the children, at the same time, they may have limited their creativity. In particular, children's final artifacts imitated or were very similar to the sample e-textile projects, as often occurs with young learners during modelling and observational learning. Along the same lines, the simplicity of children's programming might have been the result of the fact they were shown some basic sample code. Reflecting on the findings, this could have been avoided if the facilitators had shared only a single indicative artefact, perhaps without a sample of code, and/or if they had explicitly encouraged children to deviate as much as possible from the examples. Previous work in the context of e-textiles has not commented on the impact of demos and samples on creativity, especially when these demos or samples aim to motivate hands-on practice under time pressure; this is a new finding in our work that warrants further investigation.

Materiality in e-textiles being difficult to grasp

During this study, the facilitators observed difficulties related to understanding materials and their properties. Several children used conductive thread to connect electrical components and left inch-long tails as one would do with traditional handicrafts. This resulted in short circuits. In future workshops, the facilitator should allocate some time for direct instruction and triggered experimentation before the actual development of the e-textile projects to allow children to understand the properties of the materials in more depth. For example, they can explore whether a material is a conductor or insulator, its tolerance to high temperatures, softness, flexibility, etc. Such an understanding is crucial to the successful development of e-textile projects. The short duration of the workshop makes this direct instruction and triggered experimentation even more necessary, as there is little time for repeated recovery and learning from failures, despite the unquestionable value of the latter. At the same time, the facilitators need to be well-informed about the properties and limitations of available materials used in e-textile projects and be ready to assist in the manipulation of different materials. These findings are consistent with previous work that has reported similar challenges linked to the fact that the "materiality" of e-textiles is difficult to grasp (Keune, 2022; Litts et al., 2021; Rode et al., 2024).

Direct instruction and facilitation may be beneficial

From teaching circuitry concepts correctly to reinforcing a STEAM philosophy, e-textiles have great promise. Yet, under specific circumstances and contexts (e.g., limited time, novice learners with respect to e-textiles and microprocessors, novice educators regarding STEAM or making practices, lack of workshop models), e-textiles, like other innovations, might be hard to exploit. Indeed, while maker education encourages open exploration of creative ideas as well as fostering innovation with tools and materials, such processes are challenging when it comes to learning opportunities under limited time and resources. In this case, some direct instruction and in-situ scaffolding and facilitation may be required for the objectives to be achieved. This idea has also been mentioned in recent calls for a knowledge base of good practices and models to situate learning in makerspaces (Ioannou & Gravel, 2024). Our recommendation for intentional, direct instruction and scaffolding may be in tension with the concept of openness in the making ethos, which presents participants with choices around what to pursue and how to go about it; nevertheless, it might be necessary when introducing e-textiles via short-duration workshops with young learners.

An example of direct facilitation that worked very well in our context was the discussion of 2D circuit representations before the participants moved on to crafting their e-textiles. Drawing circuit diagrams on A4 paper helped the children discuss within their peers and therefore identify inconsistencies between their plans and their circuitry. Previous work has reported that children experience difficulties connecting the interface with alligator clips and then sewing it onto a planar surface (Rode et al., 2015). We believe that the practice of introducing the 2D representation was instrumental in overcoming this challenge and supporting children to create a functioning circuit, solving most of the problems via discussions between them, in addition to allowing the facilitator's input and scaffolding. We would therefore argue that some direct instruction and facilitation is not necessarily incompatible with the broader vision of openness in maker education. Teachable moments are not an undesirable compromise of the open exploration; rather, learners in such workshops can indeed pursue their own projects for which they receive in-situ support and instruction on known or (just-in-time) identified knowledge gaps.

Limitations

The present study comes with some limitations. First, the lack of a control group prevented firm conclusions on the impact of the e-textile workshop on circuitry knowledge. Circuitry knowledge gained from e-textile experiences should thus be further explored in quantitative studies following experimental designs. We further acknowledge that the e-textile projects were limited by the children's lack of coding/programming activity. This was due to a combination of factors, such as lack of software skills, little time or opportunity given to experiment with code, and the children's preference to interact with hardware rather than software. That said, our lack of evidence for advancement of coding skills should be interpreted with caution and requires further investigation. Concerns around the subjectivity and reliability of these findings, as in every qualitative piece of work, can be addressed with replication of the study and evidence of transfer of the reported findings to similar circumstances and context.

Conclusion

Despite the promising findings of prior, albeit longer, interventions structured around e-textiles, educational curriculum reform has been slow to emerge. This study examined whether significant gains in understanding can be achieved in a smaller timescale, via short-duration e-textile workshops. We found that circuitry knowledge can be advanced through short workshops. E-textile projects also seemed to encourage a range of computational making skills, assuming the children have been provided beginner-level instruction. We also documented a series of challenges related to computational making. The learning design of such workshops should be adapted to address these emerging challenges, which include the children being unwilling or not particularly adept at using software, the tension between aesthetics and constructing, the demonstration of previous e-textile projects limiting creativity, and the difficulty of dealing with the materiality of e-textiles. Direct instruction and facilitation in this case may actually be beneficial to the making activities and can help to address these challenges. Overall, findings from this study suggest that young students can benefit from their participation in short e-textile workshops. We believe that our work thus builds the field's reflective capacity around designing and facilitating introductory experiences for young learners who engage with e-textiles.

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Declarations

Conflicts of interest The authors declare that they have no conflicts of interest.

Informed consent Informed consent was obtained from all individual participants involved in the study.

Humans and animal rights This article does not contain any studies involving animals performed by any of the authors.

References

Blikstein, P., Kabayadondo, Z., Martin, A., & Fields, D. (2017). An assessment instrument of technological literacies in makerspaces and FabLabs. *Journal of Engineering Education, 106*(1), 149–175.

Fields, D. A., Kafai, Y. B., Nakajima, T., & Goode, J. (2017, October). Teaching practices for making e-textiles in high school computing classrooms. In FabLearn '17: Proceedings of the 7th Annual Conference on Creativity and Fabrication in Education (pp. 1–8). https://doi.org/10.1145/3141798.3141804

Fields, D., Jayathirtha, G., & Kafai, Y. (2019). Bugs as a nexus for emergent peer collaborations: Contextual and classroom supports for solving problems in electronic textiles. In K. Lund, G. P. Niccolai, E. Lavoué, C. Hmelo-Silver, G. Gweon, & M. Baker (Eds.), *A wide lens: Combining embodied, enactive, extended, and embedded learning in collaborative settings, 13th International Conference on Computer Supported Collaborative Learning (CSCL) 2019* (Vol. 1, pp. 472–479). International Society of the Learning Sciences.

Fields, D. A., Searle, K. A., & Kafai, Y. B. (2016). Deconstruction kits for learning: Students' collaborative debugging of electronic textile designs. *FabLearn'16: Proceedings of the 6th Annual Conference on Creativity and Fabrication in Education* (pp. 82–85). Association for Computing Machinery.

Gravel, B. E., Millner, A., Tucker-Raymond, E., Olivares, M. C., & Wagh, A. (2022). "Weebles wobble but they also commit to lifelong relationships": Teachers' transdisciplinary learning in computational play. *International Journal of STEM Education, 9*(1), 1–22.

Halverson, E., Lawson, C., Fleuchaus, E., Bakker, M., & Saplan, K. (2016). Learning circuitry through making. In The 2016 American educational research association annual meeting.

Halverson, E. R., & Sheridan, K. (2014). The maker movement in education. *Harvard Educational Review, 84*(4), 495–504.

Hébert, C., & Jenson, J. (2020). Making in schools: student learning through an e-textiles curriculum. *Discourse: Studies in the Cultural Politics of Education, 41*(5), 740–761.

Honey, M. (Ed.). (2013). Design, make, play: Growing the next generation of STEM innovators. Routledge.

Ioannou, A., & Gravel, B. (2024). Trends, tensions, and futures of maker education research: A 2025 vision for STEM+ disciplinary and transdisciplinary spaces for learning through making. *Educational Technology Research & Development*. https://doi.org/10.1007/s11423-023-10334-w

Jayathirtha, G., & Kafai, Y. B. (2019). Electronic textiles in computer science education: a synthesis of efforts to broaden participation, increase interest, and deepen learning. In Proceedings of the 50th ACM Technical Symposium on Computer Science Education (pp. 713–719).

Kafai, Y. B., & Peppler, K. A. (2014). 12 Transparency Reconsidered: Creative, Critical, and Connected Making with E-textiles. DIY citizenship: Critical making and social media, 179.

Kafai, Y., Fields, D., & Searle, K. (2014). Electronic textiles as disruptive designs: Supporting and challenging maker activities in schools. *Harvard Educational Review, 84*(4), 532–556.

Keune, A. (2022). Fabric-based computing:(Re) examining the materiality of computer science learning through fiber crafts. *KI-Künstliche Intelligenz, 36*(1), 69–72.

Litts, B. K., Kafai, Y. B., Lui, D. A., Walker, J. T., & Widman, S. A. (2017). Stitching codeable circuits: High school students' learning about circuitry and coding with electronic textiles. *Journal of Science Education and Technology, 26*(5), 494–507.

Litts, B. K., Searle, K. A., Kafai, Y. B., & Lewis, W. E. (2021). Examining the materiality and spatiality of design scaffolds in computational making. *International Journal of Child-Computer Interaction, 30*, 100295.

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

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

Papavlasopoulou, S., Giannakos, M. N., & Jaccheri, L. (2017). Empirical studies on the maker movement, a promising approach to learning: A literature review. *Entertainment Computing, 18*, 57–78.

Patton, R. M., & Knochel, A. D. (2017). Meaningful makers: Stuff, sharing, and connection in STEAM curriculum. *Art Education, 70*(1), 36–43.

Peppler, K. (2016). A review of e-textiles in education and society. *Handbook of research on the societal impact of digital media* (pp. 268–290). IGI Global.

Peppler, K., & Bender, S. (2013). Maker movement spreads innovation one project at a time. *Phi Delta Kappan, 95*(3), 22–27.

Peppler, K., & Glosson, D. (2013). *Learning about circuitry with e-textiles in after-school settings. Textile messages: dispatches from the world of E-textiles and education*. New York: Peter Lang Publishing.

Posch, I., & Fitzpatrick, G. (2018). Integrating textile materials with electronic making: Creating new tools and practices. In TEI '18: Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction (pp. 158–165). Association for Computing Machinery. https://doi.org/10.1145/3173225.3173255

Rode, J. A., Weibert, A., Marshall, A., Aal, K., von Rekowski, T., El Mimouni, H., & Booker, J. (2015). From computational thinking to computational making. In UbiComp '15: Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing (pp. 239–250). Association for Computing Machinery.

Rode, J., Feng, Y., Chandrashekar, A., Andreou, S. & Ioannou, A. (2024). Spools and Sparks: The Role of Materiality in Computational Making with E-textiles & BBC Micro:bit. Halfway to the Future 2024 (HttF 2024). ACM.

Rode, J., Barkhuus, L, & Ioannou, A (2024). Exploring Gender, Computational Making and E-Textiles using the BBC micro:bit. In Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24), May 11–16, 2024, Honolulu, HI, USA. ACM.

Searle, K. A., Fields, D. A., & Kafai, Y. B. (2016). Is sewing a "girl's sport"? Addressing gender issues in making with electronic textiles. In K. Peppler, E. Rosenfeld Halverson, & Y. Kafai (Eds.), *Makeology: Makers as learners (Volume 1)* (pp. 72–84). Routledge.

Searle, K., Tofel-Grehl, C., & Breitenstein, J. (2019). Equitable engagement in STEM: Using e-textiles to challenge the positioning of non-dominant girls in school science. *International Journal of Multicultural Education, 21*(1), 42–61.

Shepardson, D. P., & Moje, E. B. (1994). The nature of fourth graders' understandings of electric circuits. *Science Education, 78*(5), 489–514.

Timotheou, S., & Ioannou, A. (2021a). Collective creativity in STEAM Making activities. *The Journal of Educational Research, 114*(2), 130–138.

Timotheou, S., & Ioannou, A. (2021b). Learning and innovation skills in making contexts: a comprehensive analytical framework and coding scheme. *Educational Technology Research and Development*. https://doi.org/10.1007/s11423-021-10067-8

Tofel-Grehl, C., Fields, D., Searle, K., Maahs-Fladung, C., Feldon, D., Gu, G., & Sun, C. (2017). Electrifying engagement in middle school science class: Improving student interest through e-textiles. *Journal of Science Education and Technology, 26*(4), 406–417.

Wasson, B., & Kirschner, P. A. (2020). Learning design: European approaches. *TechTrends, 64*, 815–827.

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