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Research paper

Deepening children's STEM learning through making and creative writing

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ABSTRACT

Current trends demonstrate that researchers and K-12 educators are moving towards integrating computational thinking (CT) concepts outside of the computer science (CS) classroom (Lee et al., 2020). However, one of the present challenges includes a lack of engaging learning content and instruction for translating computational concepts that non-CS instructors can bring into their classrooms. Our research team developed the Grove-Blockly platform, a website that employs block-based programming and physical computing elements with simulations to support CT learning and IoT practices. We designed a 5-day workshop with the National Writing Project for students to engage in STEAM learning through making and creative writing. By examining students' learning through the processes and outcomes of making, coding, and creative writing, we aim to better understand how learning occurs at the intersections of making, writing, and computing. The findings show students' positive learning outcomes of CT and physical computing from the workshop. Mainly, students gained a deeper understanding of IoT elements (e.g., sensors, actuators) through the process of making and creative writing. This work provides empirical evidence on how students learn CT and computational practices through making and creative writing. Finally, we discuss how the engagement of STEAM practices supports and empowers students' learning of CT and physical computing through the creation of e-crafts by students.

1. Introduction

The emergence of Science, Technology, Engineering, Arts, and Mathematics (STEAM) as rising pedagogical approaches is used to promote creativity, problem-solving, and interest in STEM fields (Colucci-Gray et al., 2017). As STEM grows in popularity in K-12 schools and higher education, scholars and educators have developed a variety of pedagogical approaches and models to integrate arts-based activities into STEM curricula. However, most studies on STEAM education overlook addressing explicit arts-based learning as measurable outcomes (Perignat & Katz-Buonincontro, 2019) and prioritize only STEM and computational learning outcomes. Additionally, current STEAM approaches tend to use arts in decorative or ornamental ways and lack deep engagement in the arts discipline (Clapp & Jimenez, 2016). To better address these challenges and fill in the research gap, this study provides empirical evidence to examine art-based learning outcomes with creative writing, coding, and making.

Physical computing underpins a wide range of trending technologies such as the Internet of Things (IoT). In general, physical computing involves interactive systems that apply both hardware and software to sense and respond to the world around people. The IoT has been an evolutionary progression of the internet and continues to impact daily life. Projections indicate that the impact of IoT will involve 100 billion connected devices with a global economic impact of more than $11 trillion by 2025 (Rose et al., 2015). Many current consumer IoT applications are evident, from lighting to everyday consumer products such as coffee cups and tennis rackets, to automotive and robotics. Future applications are wide open as connectivity (to edge and cloud), protocols, miniaturization, sensors, and lower power requirements all fuel new applications that can be more ubiquitous, including wearables, smart health, water and energy management, and many other industrial and consumer applications yet to be invented (Porter & Heppelmann, 2014).

IoT tools and educational materials have been developed to teach computational concepts with physical and electronic devices in K-12 settings. However, despite the importance of IoT and its future applications, few studies have shed light on teaching IoT concepts to K-12 students using a STEAM approach (Liston et al., 2022). In particular, computational empowerment highlights the importance for students to have firsthand experience in designing with technology and to reflect

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on the computational products they create in order to gain the abilities needed to make informed choices about the future use of digital technologies (Dindler et al., 2021). Thus, our study examines the use of IoT toolkits in students' design and making processes to understand how they incorporate the elements of physical computing (e.g., LED, sound, and light sensor) into their craft designs. Additionally, we analyze students' creative writing to examine how they use the e-craft (the product of paper craft and IoT tools) they create to develop storylines that reflect the elements of IoT devices and their applications.

2. Constructionist foundations

This study drew upon perspectives on learning informed by constructionism, which supports the active process of sense-making and applying existing knowledge structures to new experiences while creating artifacts through interactions with others and objects (Kafai & Resnick, 2012). In this study, students engaged in project-based activities to create e-crafts using an IoT toolkit—Grove, and then shared their designs and challenges with each other to develop narratives in a writing-based summer program. We applied a constructionist approach to design the workshop and examined students' learning of computational concepts (e.g., loops, conditions, algorithm building), physical computing (PC) (e.g., sensors, actuators), and connections between software and hardware. We argue that the e-crafts created by students served as objects for them to think with among design, computing, and storytelling. This process then leads to meaningful engagement and learning through reflection on e-craft design and writing. According to Kafai and Burke (2014), "working across different domains – crafting, engineering, and computing – underscores the importance of seeing how concepts across a range of media and conditions" (p. 101). In this study, we examine the following research questions: (1) To what extent do students learn computational concepts, including CT and physical computing, from the STEAM project-based workshop? (2) How does the STEAM project-based approach support interdisciplinary practices among making, writing, and computing? (3) How do students incorporate IoT elements into their creative writing?

3. Computational thinking and physical computing

Wing (2006) describes computational thinking (CT) as representing the attitudes and skill set needed for solving problems, designing systems, and understanding human behavior by employing fundamental concepts of computer science. CT is a crucial skill not only for computer scientists but also for students to repurpose and apply throughout their lives. In real-world teamwork scenarios, designers, project managers, business professionals, and all other team members must be literate in computational solutions to understand and provide viable alternatives for solving general problems (Iwata et al., 2020; Ottenbreit-Leftwich & Anne, 2020)

CT involves utilizing familiar concepts and being able to think in terms of abstractions, decompositions, algorithms, evaluations, and generalizations (Selby & Woollard, 2013). One of the challenges in implementing CT in the classroom is that educators have lacked experience and understanding of the content, a flexible and engaging curriculum to guide their students, and have faced budget constraints (Mäkitalo et al., 2019). Therefore, it is essential to identify the best practices and strategies for transitioning CT from abstract concepts to deep integration in the classroom.

Current studies show that combining CT and physical computing can facilitate engagement and enhance children's programming skills in key concepts such as loops, conditionals, events, and programming practices such as remixing, testing, and debugging (Kafai & Burke, 2015). This understanding is inspired by constructionism, an approach to learning in which the design process and the "objects-to-think-with"—objects in which there is an intersection of cultural presence, embedded knowledge, and meaningful experiences. These objects are simultaneously materials in the students' environment and internalized mental structures (Papert, 2020). Constructionism is based on the idea that the most effective learning experiences are those that make students active creators, building personally meaningful artifacts, interacting with other students, and using components that support students' learning and understanding of concepts. Thus, we designed the STEAM-based workshop to introduce students to CT and physical computing activities based on a constructionist perspective. Making an artifact provides a useful learning environment in which students are encouraged to gain firsthand experience with technology, providing meaningful insights into their learning experiences (Kafai, 2006).

4. Intersections of computing, making, and creative writing

We argue that the intersection of computing and creative expression creates possibilities for transformative interdisciplinary practices between disciplines. For instance, e-textiles, products that combine electronics and fabrics, serve as effective tools for engaging women in learning Arduino programming and potentially lead to improved learning outcomes in STEM concepts. Prior studies have shown that students can better grasp the foundations of circuitry by using e-textiles than traditional circuitry construction kits (Kafai et al., 2014). By rupturing traditional norms and approaches to teaching computing, we aim to create opportunities for students to engage in interdisciplinary practices that foster productive learning in both domains, namely computational thinking and creative writing.

Studies in the field of Child–Computer Interaction (CCI) have examined the integration of storytelling into STEM education (De Paula et al., 2018; Dietz et al., 2021a; Liu & Iversen, 2022; Simões Gomes et al., 2022). Dietz et al. (2021b) investigated how storytelling could be integrated with computing education by developing and testing voice-based coding applications with youths aged six to eight. The study showed that storytelling led to better engagement and learning of computational concepts for young learners. Liu and Iversen (2022) explored the integration of embodied interaction and narrative activity through tangible programming games with a case study of one young child (a 6-year-old) and their parents to examine the effectiveness of learning programming concepts. The study revealed that embodied interaction in coding games promotes social interaction between participants (such as a parent and a child), and these interactions and conversations result in improved learning outcomes (Liu & Iversen, 2022). Building on the existing literature on computing and storytelling (e.g., Howland et al. (2007)), this study extends the computational aspect to physical computing and hands-on activity to understand how students learn CT and IoT concepts in an integrated STEAM context. Particularly, we are interested in the outcomes of creative writing in which students demonstrate not only STEAM practices but also the creativity driven by their experiences and interests.

Furthermore, computational empowerment emphasizes the importance of children analyzing and reflecting on the technology in their surroundings, particularly involving them in the processes of design, construction, and reflection based on the DORIT ("Do your Own Research In Technology") model (Dindler et al., 2020). Research has demonstrated the positive impact of hands-on activities and design-based learning on computing education (Kafai & Resnick, 2012). However, there is a lack of studies supporting how students actually reflect on the computational products they make and how this reflection leads to meaningful and productive learning experiences. Therefore, in this study, we designed a STEAM-based workshop to introduce students to IoT tools and concepts through the STEAM learning approach, integrating computing, making, and creative writing. The study seeks to provide empirical evidence of computational empowerment by examining how students reflect on their created IoT products and the narratives they develop around them.

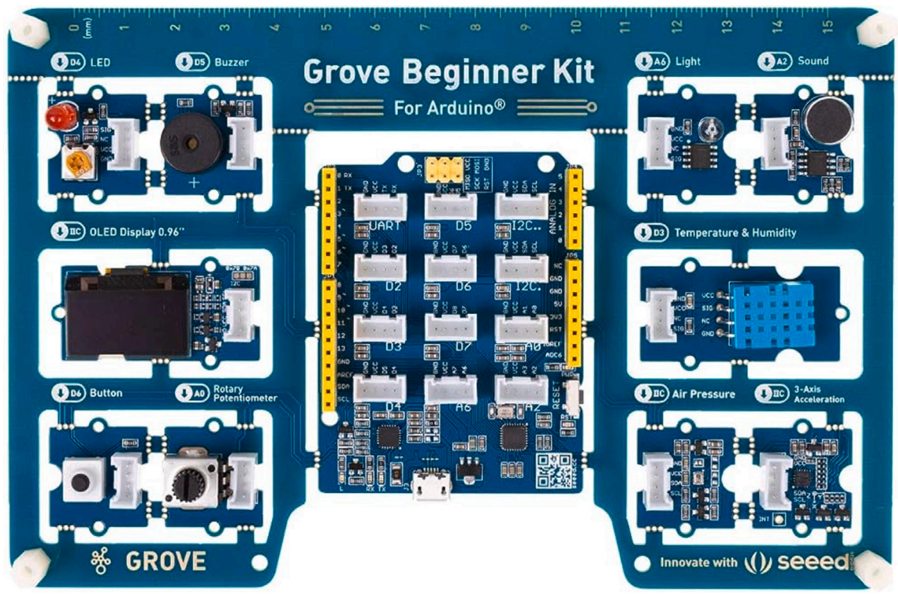


Fig. 1. Grove Beginner Kit.

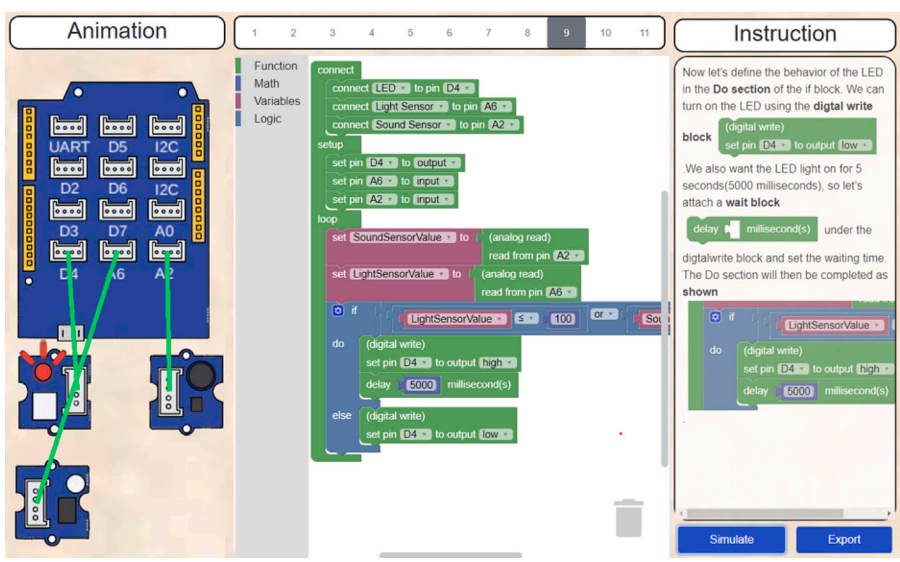


Fig. 2. Grove-Blockly platform.

5. Methods

5.1. Setting and participants

This study is part of a larger study. The data were collected from a charter middle school in Southern California, USA, during a composition-based summer camp as part of a National Writing Project program. It was a 2-week summer program, and the study took place during the first week of the program, which ran Monday to Friday for 3.5 h each day. A total of 18 students participated in the program, aged between 11 and 13 (6th to 8th grades) (F = 6, M = 10, Other = 2). Among the 16 participants who took pre- and post-tests, 19% self-identified as White, 25% as Black, 13% as Hispanic, 31% as Mixed Race, and 13% identified as Other. Students were introduced to computational concepts (e.g., functions, loops, and conditionals) and physical computing concepts (e.g., actuators, inputs, outputs) during the pre-lab exercises before diving into the e-crafting projects. For the first two days, the teacher presented activities such as lighting up an LED using a sound sensor, light sensor, and potentiometer with the designed pre-lab exercises. These processes were conducted with the Grove kit and the Grove-Blockly platform. Students then followed along with the teacher before starting the self-paced exploration of the toolkit. On the third day of the workshop, students brainstormed their design ideas in writing and drawing by incorporating IoT components and received feedback from peers and the teacher. Additionally, while they worked on the e-crafting project, they also drafted their stories and documented the process by taking pictures of their crafts. Students then used Google Docs to write their stories and included images as they preferred.

5.2. The tool and platform: Grove kit and Grove-Blockly

The Grove Beginner Kit (see Fig. 1) is a modular toolkit that includes a variety of sensors and actuators for convenient and rapid prototyping of electronics projects. Grove is a beginner-friendly kit that connects the components to the main board with plug-and-play cables. It has its own customized connectors to link different modules to the board, meaning neither soldering nor jumper wires are required. Grove-Blockly (see

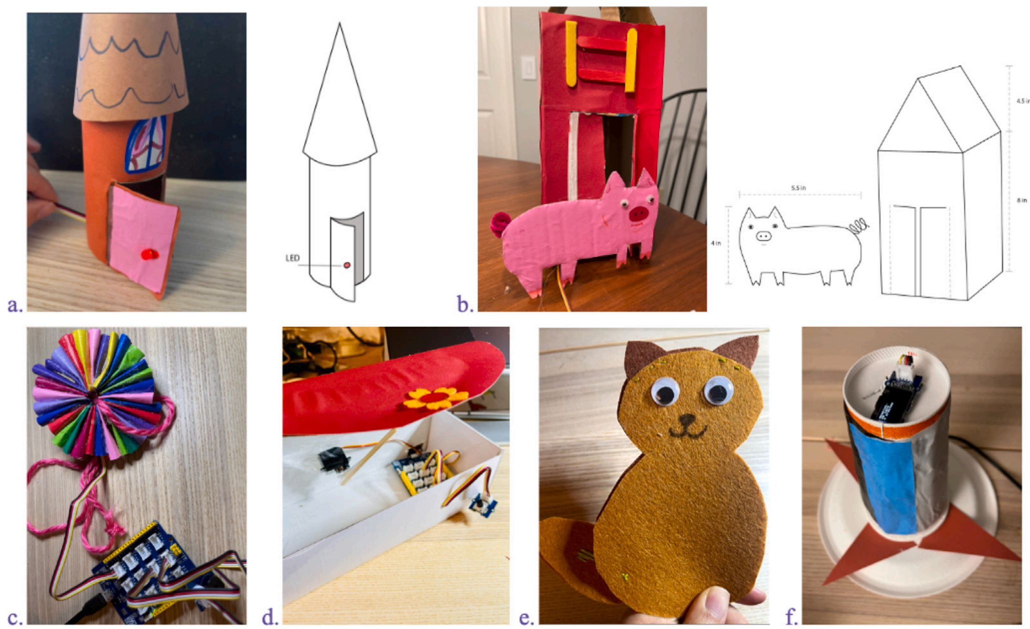


Fig. 3. Six projects examples: *2a.* Smart house, *2b.* Farm house, *2c.* Musical necklace, *2d.* Treasure chest, *2e.* Robot pet, *2f.* Rocket.

Fig. 2) is an online tool that supports the programming and simulation of the user-friendly Arduino-compatible board, the Grove Beginner Kit. The website is unique in that it enables the simulation of the uploaded code and provides feedback to students on how to correct their code. Additionally, the website provides details of each IoT component (e.g., functionality, pin, type) when the user hovers over it. It also provides real-time feedback on errors made during block programming. Users can also run their code and observe a visualization of how the code would translate into the behavior of the physical components. Grove-Blockly is also beginner-friendly and provides instructions on how to complete introductory exercises and projects.

We designed and implemented Grove-Blockly, a web-based visual programming platform, as an application built using HTML, JavaScript, and CSS. Users can drag and drop blocks, generated using Blockly, a client-side JavaScript library, to create block-based code. Visualizations for code debugging are created using Unity 3D for web applications. The code, meant to be exported, is in the Arduino programming language. Fig. 2 shows the area where students can code using the blocks. If the blocks are attached correctly, they can be nested inside each other both horizontally and vertically. Additionally, parent blocks can adjust in size to fit corresponding child blocks. In the Toolbox panel, available blocks are displayed when the user clicks on each category, such as function, math, and variables. The structure of blocks can be modified inside a pop-up panel, for example, adding an "if-else" to an "if" block. Once the blocks are completed, the user can export the script to open the code in the Arduino IDE to upload it to their physical board.

5.3. STEAM-based workshop design

The research team designed six project-based lesson plans (e.g., smart house, robot pet, spaceship, musical necklace) (see Fig. 3), which include activities on Arduino programming in Grove Blockly and paper/cardboard crafts. The lesson plans are designed for learners without programming and making experience. Each lesson plan is presented in 90 min, including the introduction of Grove kits, exercises, and a step-by-step project guide. The step-by-step instructions provide basic functional codes for the Grove kits. In this process, students had the chance to explore changing the parameters (e.g., LightSensorValue <100 to detect darkness), which were the raw analog readings from the sensors, and used to create conditional statements by choosing thresholds to trigger an action (e.g., light up the LED) and changing the time in the delay function to wait for the action to end. These explorations reinforced the concepts of conditionals, functions, logic, etc. We incorporated real-life pictures of the IoT kit, Grove, to alleviate the learning curve for Arduino programming and provide a low threshold for learners to understand electronics and coding through making.

For the creative writing, students were given a plot diagram and prompts (see Fig. 4) to support the story development, including (1) Exposition: Who are the main characters in the beginning of the story? What is the setting in the beginning of the story? (2) Conflict: What is the major problem in the story? (3) Rising action: What events happen after the exposition and before the climax? (4) Climax: When does the main character face their problem? This is the turning part of the story, things will never be the same for the character, (5) Falling action: What happens immediately after the climax? (6) Resolution: What happens at the very end of the story? Students used this guide to develop the narrative of their stories by incorporating the e-crafts they created during the workshop.

In this paper, we included data from a 5-day workshop covering topics of Grove projects and creative writing. On the first day of the workshop, students were introduced to the Grove kit and basic hardware concepts, such as inputs, outputs, and sensors. The lesson plans included three introductory exercises on the Grove-Blockly website. During the computing activity, the teacher explained CT concepts (e.g., loops, conditional logic, variables) with real-life examples that connected with the blocks used in the exercises. After completing all three exercises, students followed step-by-step instructions in Grove-Blockly to finish coding for a project, allowing them to create an artifact of their choice.

On the second day, students completed several activities, including generating pseudocode, reading and understanding code, and fixing bugs in the blocks. Additionally, students spent most of their time designing and crafting their projects. During this process, students drafted and created their e-crafts, brainstorming and creating storylines related to the e-crafts.

On the third and fourth days, students tested and debugged their designs by assembling Grove components and crafts, as well as developed their stories. They engaged in iterative processes to craft and test their e-crafts. Finally, students shared and reflected on their work and initial thoughts of the story on Padlet.com and Google Docs.

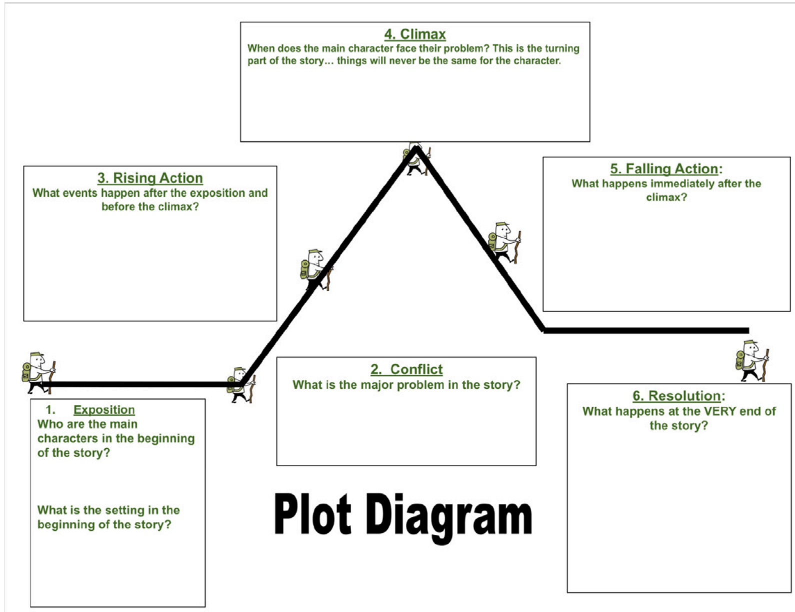


Fig. 4. The plot diagram provided by the teacher to support students' writing.

6. Data sources and analysis

6.1. Pre- and post-tests

We collected and analyzed pre- and post-tests from 16 participants. Although we had 18 student participants in the study, one student was absent for the pre-test, and one student was absent for the post-test. Consequently, these two students were excluded from the analysis of the pre- and post-tests. The pre- and post-tests were designed to examine learning gains in three aspects: (1) CT, (2) physical computing, and (3) the connections between software and hardware. At the beginning and the end of the one-week workshop, we distributed paper-based pre- and post-tests to students. Students were provided with images containing a set of code to explain the output of the block-based codes, as well as to simulate functions and draw lines across the components to accomplish tasks. (For the detailed pre-/post-test, see supplementary material "Assessment Test".) Fig. 5 shows a sample question and answer from a student (Clara, pseudonym) at the post-test stage. We then developed coding schemes to examine students' competencies in programming and IoT concepts from the pre-/post-test answers. (For the detailed coding scheme of our rubric for every question, see supplementary material "Coding Scheme".) We calculated Cohen's kappa to obtain the inter-rater reliability of the coding scheme between two graders: $k = 0.73$. The two researchers scored based on a previously decided-upon coding scheme. Finally, based on the coding results, we applied a paired sample t-test to examine statistical differences and learning gains between pre- and post-tests.

6.2. Video observations, interviews, and writing

We recorded the design and making processes of students and collected all the writing pieces from 18 students for analysis. We recorded videos with 360-degree cameras on students' desks throughout the workshop to capture their design and crafting processes. During the crafting session, three researchers conducted semi-structured interviews using iPads, recording the conversations and taking pictures of students' artifacts. We asked questions such as, "Could you explain what you are making?" and "What is your design idea?" to understand the background and motivation behind the e-craft design.

After the making session, students wrote stories based on the e-crafts they created. They used Google Docs to draft and develop their stories, starting by filling out a plot diagram that the teacher used to guide the narrative storyline.

To analyze students' writing, we began by reviewing the writing of all 18 students, then narrowed our focus to the stories of eight students due to the completion and readability of their stories. From these eight students, we selected excerpts from two students as exemplary cases to demonstrate: (a) the ways students incorporated IoT elements (e.g., LED, sound, and light sensor) into their narratives, and (b) how the e-crafts served as meaningful objects-to-think-with, providing a central role in driving the story rather than being merely a setting or random object in the story.

7. Results

In the workshop, we discovered that integrating arts through e-crafting and incorporating IoT devices leads to heightened artistic expression (i.e., creative writing) and increased STEAM engagement

7.1. Learning gains from pre- and post-test

The results indicated that all students showed improvement in the concepts of CT, PC, and CT & PC from pre- to post-tests (see Table 1). The results of learning gains from the pre-test (M = 2.75, SD = 2.98) to post-tests (M = 13.44, SD = 3.76) demonstrated a significant improvement for students in all three key competencies (i.e., CT, PC, and CT & PC) ($t = 9.47$, $p < .001$). Additionally, students' understanding of the connection between IoT components and CT concepts in the Blockly code improved from pre- to post-test (learning gains: M = 5.31, SD = 2.09, $t = 10.17$, $p < .001$). Fig. 5 provides a sample question and answer from a student, Clara (pseudonym), at the post-test stage. She connected the loop function between Grove Blockly and the physical components, potentiometer, and servo motor, from the Grove kit: "The output/outcome of the loop function by using the components I used from #1 and in the order of the blocks/code placed is first the potentiometer will need to be connected to pin A0, then the servo needs to be connected to pin D3. Next, it will send pin to A0 and to input. So it loops over would set the PotValue to analog read, read from pin A0. Set ServoAngle to map PotValue from 0 to 1023 to 0 to 180, rotate servo to servo angle degrees(s), delay 5000 ms in the end. Once you turn the potentiometer, it will make the motor move".

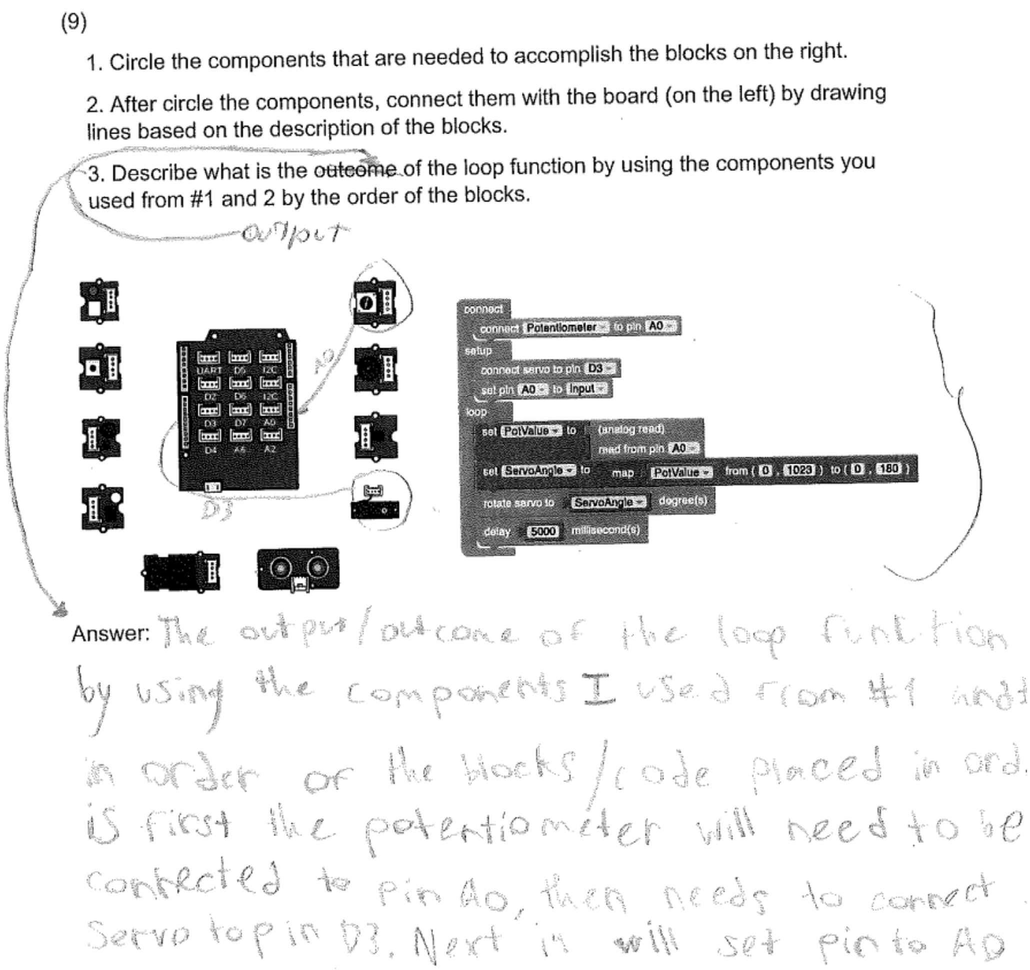


Fig. 5. Sample question and answer written by Clara from post-test (The image is cropped for space consideration).

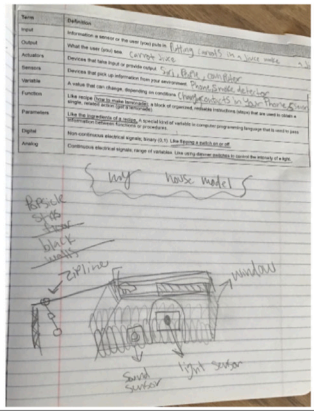
Table 1
Paired sample t-test results from the pre/post-test.

Key competencies	Gain				Pre-test		Post-test	
	M	SD	t	P	M	SD	M	SD
Total	10.69	4.51	**9.47	<.001	2.75	2.98	13.44	3.76
Computational Thinking (CT) Concepts (e.g., algorithm building, loops, conditional logic, functions)	2.06	2.14	*3.85	.002	1.00	1.32	3.06	1.73
Physical Computing (PC) IoT components and concepts (e.g., setup, connect, sensors, actuators, inputs, outputs)	3.31	1.54	**8.62	<.001	.88	1.09	4.19	.98
CT & PC Connection between IoT components with the CT concepts in the Blockly code	5.31	2.09	**10.17	<.001	.88	1.26	6.19	1.8

7.2. STEAM engagement and practices with E-craft design

The results suggested that arts integration promoted the creation of e-crafts, fostering artistic expression (i.e., storytelling) and enhancing STEAM engagement and practices. With flexible materials that required deep embodied actions, such as IoT components (sensors or actuators), students forged unique relationships between the materials, e-crafts, and computational elements. The e-crafts served as meaningful objects-to-think-with, acting as a medium for students to develop their own stories. To understand how students incorporated e-crafts into their stories by applying CT and IoT components, we examined their writing on Google Docs and reflections on Padlet.com.

Vignette 1 (see Fig. 6) illustrates an example from a student, Emma, demonstrating how she incorporated physical components (e.g., light and sound sensors) into her e-craft during the design process. In lines 1–8, Emma explained the design of her house and how she integrated the IoT components (LED, sound sensor) into the design. Additionally, she considered the spatial element when placing the components (i.e., positioning the sound sensor outside the door) to simulate real-life conditions. Furthermore, from lines 9 to 12, the researcher expressed interest in the design, prompting Emma to elaborate on the interior space of the house. In lines 13–14, there was a discussion about relocating the light sensor within the house, as shown in Fig. 7. The vignette shows how the IoT components were integrated into the design, craft, and materials, displaying the STEAM practices among arts, coding, and physical objects. Emma's work serves as an exemplary demonstration of how students integrated the Grove components into their craft design.



(1) **Emma**: And then inside, like right where the door is going to
(2) have a sound sensor, I mean, a light sensor. So that when it
(3) lights up, it slides up the whole room in the middle of the room
(4) and then behind the paper, right next to it is the sound sensor.
(5) So if you clap outside the door (sound sensor), you can see the
(6) light pop up (LED). And then this whole side of the wall is
(7) going to be windows. And then there's going to be a zip line
(8) and pool, chairs.
(9) **Researcher**: Oh pool, fancy, so it's like a rooftop pool.
(10) **Emma**: Yeah. I'm going to have wood floors, fancy wood floors
(11) with popsicle sticks. I think I might put furniture inside, but
(12) you can't really see it.
(13) **Researcher**: Maybe you can put it (light sensor) by the window.
(14) **Emma**: Oh yeah, that's the whole thing. I'm really excited.

Fig. 6. *Vignette 1*: Emma's Smart House Design.

After the testing and debugging session, students shared their reflections and initial comments on the story on Padlet.com. Emma named the house she built "Billy's Trash Mansion" and created a character named Billy, describing the design and appearance of the house (see Fig. 7). In response to peers' comments, Emma elaborated on the character and how the red LED light connected with Billy's characteristics. The narrative was intertwined with the design itself, and vice versa. Emma further developed her story in Google Docs, which she then shared with the teacher and the rest of the class.

Another student, Terry, drew from his prior experience with Minecraft to create the artifact, which he named "Jukebox for Meditation". During the design stage, he expressed his motivation for the design: "I just remember the first time I played Minecraft and built a dirt house. I recall placing torches outside. I added a bit more design in my own way. I think it mostly adds creativity, like, when you're in Minecraft, you can hear sounds. So, this could actually incorporate the sound sensors. You could hear all sorts of sounds from sound sensors, like zombies, and if it's nighttime, the light sensor detects darkness. If monsters come near the house, the light (LED) will turn on". He connected the sounds and lights in the game with the physicality and function of the sound and light sensors in the IoT toolkit. He shared his design inspiration with his classmates on Padlet.com (see Fig. 8), in which he explained how he brought the virtual "building" experience in Minecraft to the physical making and designing experiences. "The story about my house is simple but also unique. So I remember on my first world in Minecraft, I remember building a dirt house; it was really bad. Sure, that is a weird memory, but it gives me so much nostalgia and makes me want to go back, so I built the house to give me that feeling back". Building on this inspiration, he then developed a story based on the design of the house and the IoT components. Fig. 9 provides an excerpt of his writing, in which he mentioned the creation of "Jukebox" by the protagonist of his story, Steve. The story started with a chapter from day one to day four about Steven's adventure, and then jumped to day eighty-five and eighty-six: "Day eighty six: Steve is at his house. he (He) don't (doesn't) know what to do now,but he thought of one more thing in mind before he's at peace. He builded(built) a jukebox, and played the music he found during those days, now Steve is at peace. But not for long...".

7.3. Storytelling and STEAM learning

At the end of the workshop, each student developed their own storylines based on the e-crafts they created. We reviewed a total of 18 students' writing to examine how they integrated the components of physical computing (e.g., LED, sound sensor, light sensor) into the narratives. The most common story genre was fantasy. For example, some students wrote about a mysterious music box that makes people fall in love or a magic music box that transports people to different times and spaces. Students often included family members as main characters and developed storylines around their relationships (e.g., grandmother and granddaughter; sisters and brothers; father and his children). Additionally, most students used the e-crafts as the central object or setting of their stories (e.g., a smart house with LED lights, sound sensors, and light sensors, inspired by a Minecraft theme).

Building on the storylines, the e-crafts were employed and played a crucial role in their stories. Overall, the most popular e-crafts created by students were music boxes (33%) and rockets (17%). In their writing, the most referenced electronic component was the buzzer (47%), as students often mentioned that the craft produces sound and then the LED (28%). For music boxes, students often associated them with fantasy stories (e.g., the box is positioned as an agent for change and dream fulfillment for the characters in a story). For rockets, the theme was associated with science fiction stories. The e-crafts were usually the center of the stories and directly connected with the protagonists in the narrative. For instance, the e-craft was the inheritance from a family member and weapons or objects that aid to rescue the world or save the protagonists in the stories. Additionally, the e-crafts were positioned as a positive force that helped the protagonist to overcome obstacles. Most e-crafts were described before or after text with images related to the stories.

To illustrate how students incorporated their e-crafts into their narrative writing, we provide two vignettes below from Caleb and Rachel (pseudonyms) as exemplary cases to demonstrate how the object was positioned as central components of the storyline. First, Caleb's story was about a family that is neglected by townsfolk and loses their house because of an accident caused by a misuse of electronic components. Fig. 10 shows a screenshot of his writing. Fig. 10 serves as an exemplary work for how youth integrated the IoT components into their prototype, which is reflected in the writing.

The sentences highlighted in yellow in the figure read: "...But when the lights went out, the family tried to fix the light, but one of the family members cut the wire, and the light fell off. The light started a fire, so the family ran out of the house..." The electronic components of the e-crafts were embedded in the stories and most of the time were the fuel to drive the story.

Caleb applied LEDs, a sound sensor, and a light sensor, along with colored paper and wooden sticks for decoration, to build the house. Additionally, the house he created detects sounds from a sound sensor, and the LED lights up accordingly. In Excerpt 1, Caleb describes the e-craft as an old house, the primary setting of the story.

For the main exposition of the story, a family is portrayed pessimistically due to their misbehavior towards their neighbors, resulting in neglect by the community (Lines 1–5). Caleb incorporated the functionality of physical computing into the storyline with the LED serving

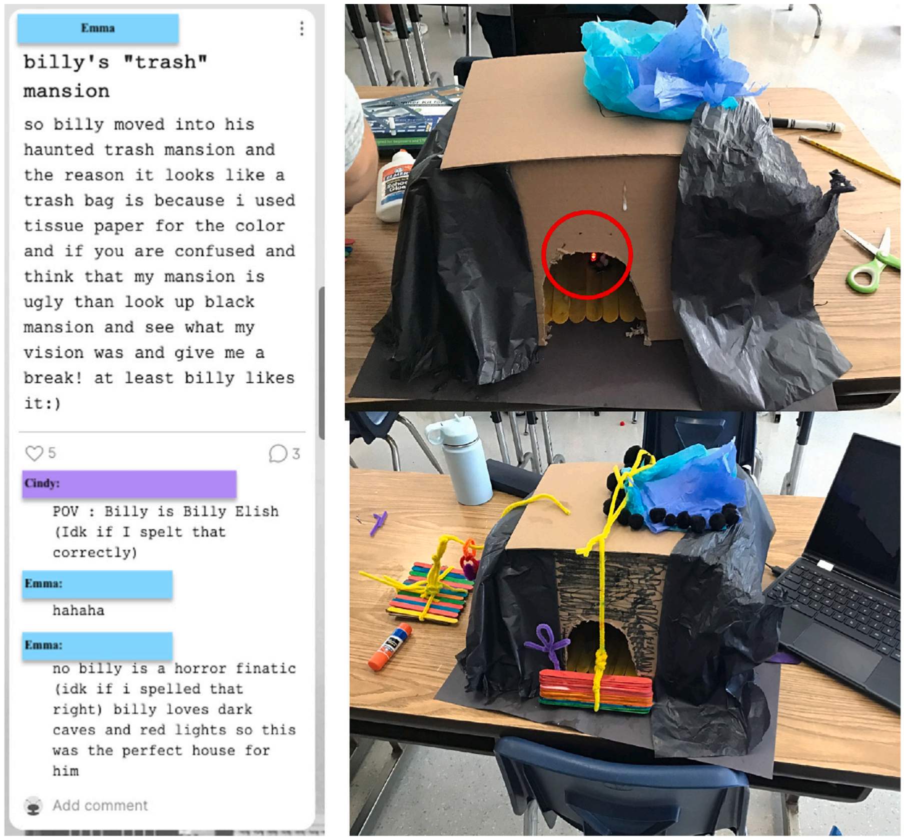


Fig. 7. *Left*: Emma's post and comments on Padlet.com *Right-Top*: Testing the light sensor with the craft. *Right-Bottom*: Emma's smart house design, Billy's Trash Mansion.

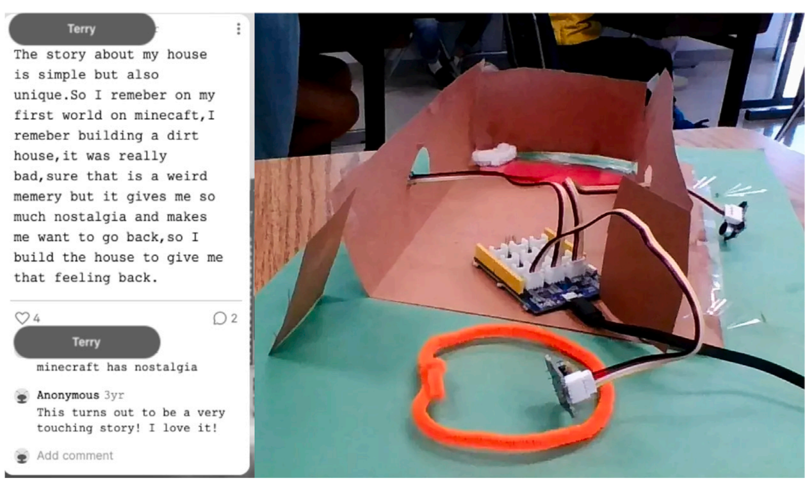


Fig. 8. *Left*:Terry's post and comments on Padlet.com *Right*: Terry's IoT craft inspired by Minecraft.

as a metaphor for light and fire (Lines 6–9). The climax began with the family escaping the tragic scene, leaving behind the fire and a burned house (Lines 7–10). Interestingly, in Caleb's story, these IoT components were not just physical materials. Instead, he treated these IoT components as metaphors that contributed to the narrative of his story (e.g., LED light means a fire in the story) like a theater prop design. The e-craft, described as a flimsy house, aligns with his storyline about the main characters, a family who went bankrupt. They had lived a good life before moving into the flimsy house. The family is so pessimistic about their reality and has a bad reputation among their town neighbors due to how they treat others in their community. The functionality of the physical computer is indirectly depicted in the story, with an LED light representing a fire that leads to the climax of the story.

In Rachel's writing, the e-craft (i.e., the music box) (Fig. 11) drove the story of the main character, Nicole, and her relationship with her grandmother and other family members. Her story, titled 'The Magic Music Box', was written in first-person perspective with the timeline divided into periods before and after Nicole's grandmother passed away. The story began with a conversation between Nicole and her grandmother in a hospital. Below is an excerpt from her writing:

Excerpt 2 began with Rachel introducing the storyline, starting with a conversation between Nicole, the main character, and her grandmother (Lines 1–6). She described the physical appearance of the music

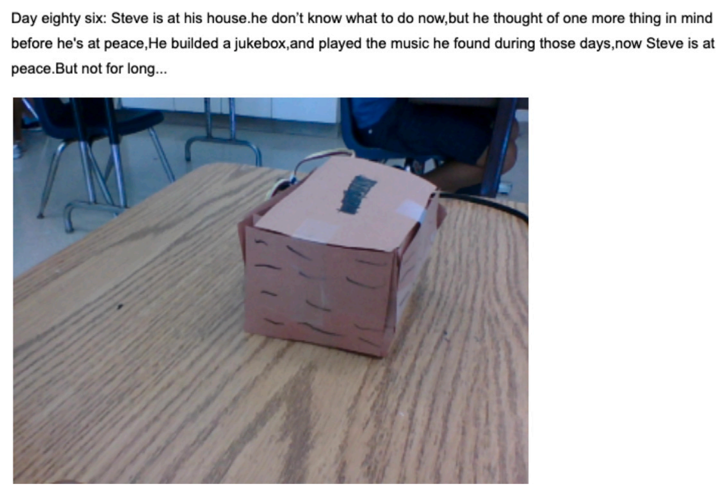
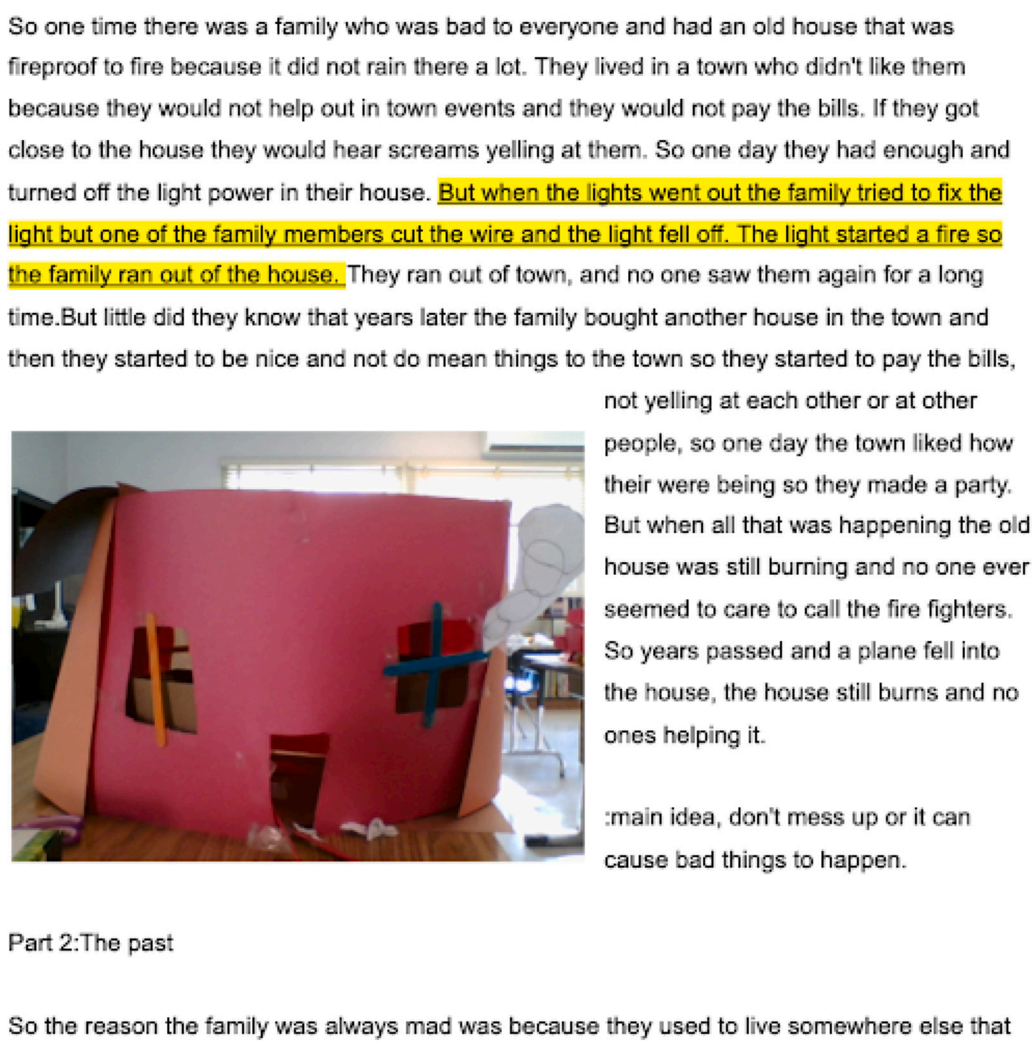

Day eighty six: Steve is at his house.he don't know what to do now,but he thought of one more thing in mind before he's at peace,He builded a jukebox,and played the music he found during those days,now Steve is at peace.But not for long...

Fig. 9. An Excerpt of Terry's story.


So one time there was a family who was bad to everyone and had an old house that was fireproof to fire because it did not rain there a lot. They lived in a town who didn't like them because they would not help out in town events and they would not pay the bills. If they got close to the house they would hear screams yelling at them. So one day they had enough and turned off the light power in their house. But when the lights went out the family tried to fix the light but one of the family members cut the wire and the light fell off. The light started a fire so the family ran out of the house. They ran out of town, and no one saw them again for a long time.But little did they know that years later the family bought another house in the town and then they started to be nice and not do mean things to the town so they started to pay the bills, not yelling at each other or at other people, so one day the town liked how their were being so they made a party. But when all that was happening the old house was still burning and no one ever seemed to care to call the fire fighters. So years passed and a plane fell into the house, the house still burns and no ones helping it.

:main idea, don't mess up or it can cause bad things to happen.

Part 2:The past

So the reason the family was always mad was because they used to live somewhere else that

Fig. 10. A screenshot of Caleb's story – "Whatever you want to call it".

box in detail, from top to bottom, including the colors she used to build it (Lines 7–12). She then introduced the function of the music box, stating "press the button" and "The song, Ode to Joy" played (Lines 13–14). This reflected two components of Grove kits: the push button and buzzer that she programmed using Grove-Blockly. Although we were unsure if she attempted to modify the code for the song included in Grove-Blockly, it was possible for her to adapt the provided music script and make changes. Rachel continued her story with Nicole's new high school life and her meeting with a friend, Shelly, who later referred to the music box as a "magic music box". Excerpt 3 demonstrated how

Excerpt 1. An excerpt of Caleb's story – "Whatever you want to call it"

1	So one time there was a family who was bad to everyone and had an old
2	house that was fireproof to fire because it did not rain there a lot.
3	They lived in a town who didn't like them because they would not help out
4	in town events and they would not pay the bills.
5	If they got close to the house they would hear screams yelling at them.
6	So one day they had enough and turned off the light power in their house.
7	But when the lights went out the family tried to fix the light but one of the
8	family members cut the wire and the light fell off.
9	The light started a fire so the family ran out of the house.
10	They ran out of town, and no one saw them again for a long time.

Fig. 11. The music box in Rachel's story.

Rachel incorporated the background and history of the music box into the narrative, ultimately leading to a new friendship between Nicole and Shelly.

In Excerpt 3, Rachel introduces a new character, Shelly, who happens to know Nichole's grandmother and the background of the music box (Lines 6–15). In particular, she referred to it as the "magic music box" and shared the story behind it with Nichole. Nichole and Shelly became good friends and supported each other, overcoming some of the obstacles in the story (i.e., bullying) at their school. One day, Shelly invited Nichole to have a sleepover at her home, and Nichole brought the music box with her.

Towards the end of the story chapter, Excerpt 4 illustrates how the magic music box propelled the narrative and introduced a new plot twist. The story's climax occurs when the music box glows in Shelly's room, causing both characters to fall into "some type of portal" (Lines 3–8). The magic music box then led them to The World of Magic and she ended the story with a cliffhanger. In Rachel's story, the artifact appeared across the story plots from beginning to end. The music box served as the primary object that initiated the storyline, progressed towards the climax, and ultimately propelled the story from beginning to end. In particular, she portrayed the magic music box as an object crafted from the real-life e-craft she created. The function of the object was embedded into the storyline as magic elements (i.e., a music box that glows).

8. Discussion and implications

This study illustrates how a STEAM project-based learning approach can deepen students' understanding of CT and physical computing through hands-on making and creative writing. The results of pre- and post-test showed a total improvement of up to 79.5% in learning gains across key competencies in CT and PC. In particular, we utilized our Grove-Blockly platform to introduce CT and integrate it with the Grove kits, allowing students to create e-crafts based on their interests. The e-crafts were both a medium and catalyst to support the emergence of STEAM learning and practices while students are engaged with coding, crafting, and writing. The results showed how students were able to reconcile their old (creative writing) and new (CT and PC) knowledge throughout the iterative design processes. The results indicated that students integrated various IoT components into their stories by applying CT concepts. For instance, Caleb described a scene in his story where the family 'ran off and the power fell off' during a fire, drawing inspiration from the functionality of the Smart-House project. Additionally, Rachel wrote about a magic music box given by her grandmother before her passing away and left with the message that it would "start the song if she would just press the button", which was inspired by the algorithm (if-then) from the Musical Necklace project.

Students not only designed the e-crafts based on the application of IoT components but also generated stories and meanings associated with the e-crafts as they constructed them. The physical attributes of the IoT kits played a crucial role in guiding the design of e-crafts and storytelling. Throughout the iterative processes, students had to make several design decisions: How to position the components given the length of their cables connecting them to the Grove board? How to position the components to be fixed or stable inside their construction? How to fit their components in an effective way to fit their narrative and purpose? For instance, in the Smart House project, students faced the challenge of positioning the light sensor to ensure that the roof of the house did not obstruct it, thereby keeping the LED continuously illuminated. Then, students created windows, balconies, removable roofs, to complete their projects as planned. In doing so, they reinforced their understanding of the functionality of the sensors. Through active engagement in decision-making and problem-solving, students enhanced their comprehension of abstract CT concepts by applying them to physical materials and hands-on making.

The study does not aim to argue that the STEAM-based approach is superior to the non-STEAM-based approach. Instead, the goal of the study is to provide empirical evidence demonstrating how students deepen their understanding of IoT components and computing through making and writing. The integration of STEAM activities allows for the complementary enhancement of CT and computational empowerment, fostering critical thinking among students as they interact with technology. Additionally, firsthand experience with technology, through the creation of personally meaningful IoT products, provided students with opportunities for reflection and design. This process required decision-making and deeper engagement with the materials. Students grew emotional attachments and self-satisfaction while they engaged these practices. During the group discussion on the last day of the workshop, Caleb expressed that he had "enjoyed [the activities] much more than he expected" and that once he started he "wanted to keep going". While only a few students had previous experience with block-based programming (e.g., Scratch), those students mentioned that the hands-on aspect of IoTs made the relationship of sensors-code easier to understand. Clara mentioned that she had some prior experience with

Excerpt 2. The beginning of Rachel's story – "The Magic Music Box"

"So Nicole...I've been really sick lately."
"I know."
"So in case I pass…"
"Don't say that! You'll live! Your strong Grandma!"
"Alright, alright. But just in case...I want to give you something." Grandma replied. She turned on her bed and reached down to the floor beside her.
She picked up a box. It was very colorful.
One side had red and green stripes, another had orange and purple, one had purple and yellow, and the last side was green, yellow, red, and purple striped. The bottom of it goes like this. Green, blue, green, yellow, green, orange, green, purple.
The top of it was striped as well. She gave it to me and I opened it.
"Press the button." Grandma said.
I pressed the button. The song, Ode to Joy turned on. I realised it was a music box.
"Thanks so much Grandma!" I replied.

Excerpt 3. An excerpt includes the new character of the story, Shelly.

"Oh, class!" the teacher exclaimed. "We have a new student here! Would you please introduce yourself?"
"Oh okay. I'm Nicole, and I just moved here a few years after my grandma died!" I said.
Some of the students whispered to each other when I said my grandma died.
"I'm sorry for your loss…. Your seat is over there behind Shelly! My name is Mrs. Mgee!" the teacher said.
Shelly! I'm guessing that's the girl who has the locker next to Principal Dere's office.
Shelly raised her hand and I sat behind her.
"Hi I'm Shelly-" Shelly started.
"I'm Nicole Johnson." I replied.
"Wait a minute...your grandma was Judy Johnson?!" Shelly asked.
"Yeah? How did you know that?" I asked.
"She was very famous!" Shelly replied. "She was known for her magic music boxes! There's only 5 in the world! Legend has it that if all five are grouped together, something magical will happen!"
"Wow! I got a music box from my grandma before she died. Do you think it's magical?"
"Is it a bunch of different colors?"
"Yes!"

similar activities on the computer, but found it challenging initially. However, as she gained a better understanding of the sensors, she found the process easier to grasp. She said: "I've done something a little bit similar to this but it's just on the computer that we're just doing the coding…It was a little bit hard on me at first but now all of sudden when I understand [the sensors] as it goes on". Dylan also concluded that the back and forth and struggle helped him learn more: "I feel like I know a little bit more, because of all the frustration and the situation that went through it". Matt expressed his satisfaction at completing his spaceship and thought his next steps would be to continue: "I'm going to use this code and modify it now. I'm going to use it to test other code. I hope I don't literally fry this [board]. [I'm] not much of a modifier…but I want to try". Rachel also mentioned she had been working on another project from the website at home and she had been "super happy the buzzer was working".

Finally, students' stories served as learning outcomes, demonstrating how various practices intersected and resulted in meaningful products. The practice of creative writing is particularly interesting because students typically bring inspiration from "pop-culture". For instance, students drew inspiration from games such as Minecraft, Roblox, and Among Us to build their e-crafts. They also found inspiration from anime such as Attack on Titan and music artists. By encouraging this type of cross-over among interest, media, and arts, STEAM educators can promote meaningful and productive learning experiences. E-crafts served as a medium for students to inherently engage in STEAM practices. Using e-crafts provided a meaningful and playful context for students to assign roles and functions to electrical components.

As STEAM learning and practices are both dynamic and holistic, this study aims to provide productive insights to inform the assessment and evaluation of STEAM learning. Leveraging arts practices, the

Excerpt 4. The Magic Music Box and the World of Magic

> ""Do you have the magical music box?" Shelly asked.
> "Yeah!" I took out the box and set it on her bed. We were sitting on it.
> "That's weird. Does the box usually glow?" Shelly asked.
> "I've never seen that before."
> The music box started glowing brighter and brighter until the light of the box was the only thing in the room. The bed disappeared and we started falling all the way down some type of portal.
> "AHHHHHHHHHH!" we screamed.
> . . .
> When we woke up, we saw this weird woodland creature that's from a fairytale.
> "Where are we?" Shelly asked.
> "Hi!" the creature said. "I'm Lanston, and welcome to The World of Magic, Princess! We have been waiting for you!"
> "Shelly, I don't think we are in California anymore…." I exclaimed.
> "YOU THINK?!" Shelly exclaimed.
> To Be Continued…

STEAM learning approach encouraged students to further engage with computational concepts and potentially broaden their participation in STEM. Regarding computational empowerment, these practices are critical for the coming generation. They need to gain the capacity and skills to make informed choices and think critically about surrounding technology as citizens in a digitized society (Dindler et al., 2020). For future work, we will examine STEAM learning with a variety of cross-disciplinary practices to understand how students integrate the concepts and skills they learned in different STEAM settings to advance the evaluation and assessment of STEAM education and curriculum.

Selection and participation of children

Children participated the 5-day workshop were part of the host school when they attended the summer course. They were told that the work was part of an NSF-funded project, and the workshop was co-designed with National Writing Project. We gathered consent letter from the president of the host school. We provided the school both parental consent and children assent form and collected the physical copies with their signatures. Children and parents were told that the participation of the workshop was voluntarily, and they were able to refuse to participate and withdraw from the study at any time in the process. We video recorded children's interactions with the different materials and tools, collected interviews and photographs of their projects. Children were told that if their photos of projects might be used but their names would be removed.

CRediT authorship contribution statement

Joey Huang: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Ariel Han:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Ana Villanueva:** Data curation, Software, Writing – original draft. **Ziyi Liu:** Software. **Zhengzhe Zhu:** Software. **Karthik Ramani:** Supervision, Funding acquisition. **Kylie Peppler:** Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Update

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Erratum regarding missing Declaration of Competing Interest statements in previously published articles

Declaration of Competing Interest statements were not included in the published version of the following articles that appeared in previous issues of International Journal of Child-Computer Interaction.

The appropriate Declaration/Competing Interest statements, provided by the Authors, are included below.

"How block-based, text-based, and hybrid block/text modalities shape novice programming practices" (International Journal of Child-Computer Interaction 17, (2018) 83–92) https://doi.org/10.1016/j.ijcci.2018.04.005. Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this paper.

"Socializers, achievers or both? Value-based roles of children in technology design projects" (International Journal of Child-Computer Interaction 17, (2018), 39–49) https://doi.org/10.1016/j.ijcci.2018.04.004. Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this paper.

"A comparative study into how pupils can play different roles in co-design activities" (International Journal of Child-Computer Interaction 17, (2018), 28–38) https://doi.org/10.1016/j.ijcci.2018.04.003 Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this paper.

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