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CyberPLAYce—A tangible, interactive learning tool fostering children's computational thinking through storytelling

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ABSTRACT

The learning environment plays a critical role in a child's life, affecting both cognitive development and effectiveness in work or play. As the boundary between physical and digital worlds blurs, there is a need for new digital tools and physical environments to support the everyday, cyber–physical interactions of children. This paper presents a *Research-through-Design* example of CyberPLAYce, a tangible, interactive, learning construction kit for children supporting storytelling and computational thinking (CT). The construction kit facilitates and enhances child-to-child, child-to-machine, and child-to-environment interactions through semi-structured play. It offers young students the opportunity to materialize their ideas through the construction of cyber–physical story algorithms allowing them to physically alter story segments while constructing and enhancing the storyline. The CyberPLAYce research places an emphasis on the importance of employing tangible learning tools in order to enhance children's active engagement. We focus on the motivations for CyberPLAYce, its participatory design, and results of an empirical study concerning CT with 8-12 year-old storytellers in a classroom setting. Results from the study suggest that cyber–physical activities afforded by CyberPLAYce cultivate engaged storytelling and CT practices in children. This multidisciplinary design-research contributes to construction tools for children, cyber–physical storytelling and story-construction activities, and tangible computing and programming activities that support CT.

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It is no longer possible to think about education and the process of knowledge construction separate from a large number of technological and social factors. Research indicates that the integration of various modes of expression, communication, and interaction can enhance a human's learning experience and cognitive engagement with the world [1,2]. Technological advancements influence learning through the verbal, visual, and spatial affordances of tools, while various forms of media, including paper, screens and spaces, shift learning from single modality to multimodality. Multimodal activities offer students the opportunity to spontaneously combine and move across sounds, lights, texts, images, movements, and even aromas in order to solve a real-world problem or complete a real-world task [3].

At the same time, we have increasingly complex problems requiring new sets of skills and tools to solve multifaceted, complex issues. Computational thinking (CT) is considered a vehicle to "magnify problem-solving skills needed to address authentic, real-world issues" to assist today's children in meeting "workforce demands of the future" [4]. The ability to express ideas and solve problems computationally is increasingly becoming an important skill. Computational Thinking is thought to be a gateway to success for student achievement in the digital age, to gaining comprehensive, technology-driven knowledge and skills, and to honing imaginative expression [5–8]. Since collaboration and CT practices serve as pathways for employability and economic growth, exposing students to CT practices at an early age allows them to cultivate this practice and explore its capacities. Importantly, CT promises, "to help solve some of the most pressing, intractable problems of our time" [4].

One way to capitalize on the power of multimodal learning, and the need to hone CT practices to solve problems is through play. "*For as long as we know, children educated themselves through self-directed play and exploration*" [9]. The idea of learning through play and exploration initially came about "*during our evolution as hunter-gatherers, to serve the needs of education. Adults in hunter gatherer cultures allowed children almost unlimited freedom to play and explore on their own because they recognized that those activities are children's natural ways of learning*" [9]. Research shows that well-developed play has positive impacts on various areas of child development, such as children's social skills, emerging

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Fig. 1. Children playing with CyberPLAYce during the empirical study.

mathematical ability, mastery of early literacy concepts, and self-regulation [10]. From a sociocultural standpoint, the notion of play involves an imaginary situation and a set of rules [11]. The imaginary setting offers a space for children to explore and experience the rules in ways that were not previously available to them. In this way, play can function as an informal inquiry [12], encouraging children to spend more time in discussing and articulating the rules of a play setting [13]. In such settings, play works as a social, exploratory, and collaborative task that enhances and scaffolds personal and collective expressions.

This research details how CyberPLAYce (Fig. 1), a novel play space of multimodal, interactive tools, allows students to discover, manipulate, and create designed, interdisciplinary, and imaginative activities. Our investigation focused on the design and evaluation of a portable, cyber–physical, tangible construction suite for children to enhance their CT capacities through storytelling. We argue that the tangible approach is essential to meet these requirements. By tangible, we mean that CyberPLAYce integrates graspable and touchable elements while involving the physical location, order, orientation, and the geometry of the elements [3,14].

A further aim of CyberPLAYce is to enrich playful learning by offering engaging activities, sequences, sorted items, and cyber–physical stories. Student choice is an integral component of the design, using simulated environments and experiences, matched to curricula, collaborative play, and the sharing of student creations.

CyberPLAYce is a learning tool comprised of several modules and panels with embedded electronics. During CyberPLAYce activities, students collectively reconstruct a given story or construct their own story to solve a given problem. Students match story segments to electronic modules while plugging the modules into larger panels to compose a three-dimensional story algorithm. This allows students to think about different story configurations while connecting large panels together. At the same time, the plug-and-play activity offers students instant feedback through the embedded electronics. This may range from the illustration of temperature and distance variations to light and sound effects. For example, a child might use CyberPLAYce to construct a story about a 'Clean Energy Center' where different CyberPLAYce panels and modules resemble environmental technologies such as wind turbines, solar panels, and cooling systems.

Our goal is to bridge storytelling and CT experiences through the design, implementation, and evaluation of a reconfigurable, computationally-embedded, plug-and-play environment that students use to create imaginative activities. Our research team investigates how cyber–physical technologies, resources, and learning environments might effectively enhance playful learning experience of young learners, and hone their CT capacities. After creating a prototype of CyberPLAYce, our research questions investigated (1) how it supported children's storytelling experiences and (2) how it enhanced children's computational thinking.

1. Literature informing the empirical study

CyberPLAYce was conceived from notions of constructivism and constructionism, cyber–physical play, and CT practices. Pertinent literature is reviewed based on these research questions:

(1) How does CyberPLAYce support children's storytelling experience?
(2) How does CyberPLAYce enhance children's computational thinking through playful activities?

1.1. Constructivism, constructionism, and contextualized learning

Constructivism [15] is a theory of learning that offers a compelling approach to education; it considers children's interactions with the world as they actively construct knowledge. Piaget noted that knowledge is not simply transferred from teacher to pupil, but actively constructed in the minds of children [16]. Seymour Papert built on Piaget's work, proposing *constructionism*, wherein learning is viewed as a multi-layered concept that takes the idea of learning-by-making to a more profound and complex level, and attends to the process of learning and design by the creation of artifacts [17]. Kafai and Resnick argued that "*children don't get the ideas, they make ideas*" [17]. Moreover, children are likely to create new ideas and perform imaginative problem-solving when they are actively constructing knowledge and interacting with external artifacts, such as learning tools and robots.

Although some researchers argue that Piaget did not attribute much to the context of a learner's interaction, Ackermann [18] noted, "integrating both views can enrich our understanding of how people learn and grow". For Ackerman, Piaget's constructivism helps us understand how the thinking of children evolves through their active participation with others and the world, while Papert's constructionism is focused on the use and social conversation around making artifacts such as tools and media to assist in building knowledge. Ackerman suggests, and we agree, that both perspectives are useful in illuminating the processes of 'how' children make sense of their experiences.

Furthermore, psychologists and cognitive scientists propose that knowledge is essentially situated, and thus should not be separated from the context in which it is constructed and realized [19–21]. This interest in knowledge-construction within the context of learning has directed many researchers in developmental psychology and other areas to concentrate on learners' interaction with contextual elements. Several education specialists and scientists noted that, *to know is to relate*, and *to know better*, and *to obtain more profound understanding* is to *learn-in-relation* [22]. These perspectives consider the importance of bringing subjectivity to the center of consideration where knowledge is constructed, transferred, and exchanged.

Piaget hypothesized a functional theory of intelligence as a way to understand how people regulate their interactions with contextual elements. He focused on the *assimilative* role of adaptation by putting an emphasis on the reflection of self-in-context as a key to learning, where there is a capacity to regulate interactions in relation to contextual elements [23]. Children's interaction with the world follows similar ideas about functional theory of intelligence, and the relationship to context and an understanding of the world.

The CyberPLAYce research considers both constructivist and constructionist theories and approaches, building on Piaget's [16] theory of intelligence where knowledge is constructed by a continuous interaction between the child and context, and Papert's thoughts regarding interacting with tools to mediate an ongoing

understanding. The child gains such understandings from the subject and context through active construction and re-construction of knowledge. These theories guided the research and provided a foundation to view children as learners in a social setting where there is an interaction between children, environment, and shared artifacts.

1.2. Interactive knowledge construction through storytelling

In recent years, children's use of digital media and related technologies outside of school has been well documented suggesting children's content creation habits are valuable for learning [24]. Researchers have noted that most children are actively engaged in participatory culture of digital production and meaning-making through technologies such as video-creation and sharing, game play and game design, animation, digital storytelling, and photo-sharing [24,25]. Contemporary theorists point to social networks, learner-centered cyber–physical spaces, and games as conduits to life-long learning, often drawing on socio-constructivist theory, to demonstrate that technology-rich environments facilitate learning [26,27].

Recent projects such as Digital Youth Divas [28] rely on interest-based learning (i.e. students' interest in technology-enhanced learning), which connect students' existing knowledge to the creation of stories through digital artifacts while strengthening computational storytelling. Others have pointed to interactive storytelling and creative expression as an aspect of coding in online communities such as Scratch [29]. In these studies, students used Scratch and other interactive media such as games, puzzles, and visual graphics to create or retell stories. The research found that the interactive storytelling with media promoted the use of programming concepts and techniques.

This prior research has two implications for formal education: First, educators should capitalize on students' interest in learning with technology and media production to increase engagement. Second, researchers and educators should understand the way in which children think about knowledge in relation to context, as research shows that learning environments are significant in children's understandings of subject matter.

Kafai [17] posited that although learning can be joyful to many children, a lot of educational activities do not necessarily strengthen understandings of the nature for learning subject matter. To enhance a learning activity and promote knowledge acquisition, Kafai [17] suggested five key questions for which the responses to such questions can provide a tool or language to communicate the potential influence of a learning activity:

1. *Is the activity interesting, fun, and motivating?*
2. *How does the activity portray knowledge?*
3. *What does the activity say about who can be the expert within the subject?*
4. *Does the activity offer insight into how new knowledge is constructed?*
5. *Does the provided experience connect children's strengths and abilities to the subject?* [17]

Kafai's five questions offered the CyberPLAYce team a guiding framework for developing and evaluating a cyber–physical learning tool involving fun and engaging activities for children to give form to their thoughts through the physical construction of stories and ideas.

1.2.1. Cyber–physical technologies facilitating interactive, semi-structured play

Gee [30] discusses the educative value of learning through play by explaining that this sort of pleasurable activity allows for horizontal learning where the child 'mucks around' and tries out various possibilities, takes risks, and makes connections to what they already know. He describes horizontal, play-based learning as important as vertical learning that requires ratcheting up of skills. This perspective is valuable, but not entirely new. The potential for tangibles to encourage cognitive engagement in which children playfully explore the local environment and make connections to concepts has been examined for decades [31]. Opportunities to use cyber–physical tools with semi-structured play, where some guidance exists but activities are open-ended enough to allow for exploration and new ways of thinking, have been studied in recent years to investigate their potential for encouraging engineering thinking, mathematical reasoning, and to deliver educational content [32]. For example, the concept of embedded phenomena [33] was used in science classrooms to demonstrate a novel way of using technology (PCs or tablet computers), classroom space (simulating areas such as epicenters or insect migration and environments), and time (duration and persistence when collecting data or observing phenomena) to assist students in learning particular science concepts. The researchers then provided a framework for practitioners to use with the existing curricula that positively influenced students' participation, skill acquisition, and attitude towards science.

In a 2003 study [34] researchers discovered that playful learning with an adventure game centered on a virtual, imaginary creature was highly engaging and encouraged young learners' exploration, wonderment, reflection, creativity, and collaboration through the use of digitized and tangible objects, ultimately assisting them in achieving goals to solve problems within the game. Another study [35] documented how extending KidPad, a collaborative 2-D drawing tool augmented with a sensor-controlled "magic carpet", helped children to retell stories for audiences in a performance-based, imaginative, and collaborative way, supporting the social nature of learning in primary classrooms. The researchers proposed this type of interactive learning could engage children by drawing on what they know and what they enjoy.

A more recent study that focused on middle school students' productive play when using low-cost tangible construction kits and gaming environments to design artifacts and create educational experiences for their peers demonstrated positive results [36]. The students engaged in semi-structured play activities by creating on arcade for their peers with a Makey and Scratch. Besides noting students' perceptions of fun and engagement, the researchers reported how the arcade provided "a meaningful context in which participants were able to test and view their work" (p. 441), and suggested the tools and arcade provided students with an authentic audience, allowing them to see and make connections between their designs and learning for both their peers and themselves.

These research-based examples demonstrate that when hands-on activities are integrated in a playful manner, they engage children's senses and encourage them to imagine, manipulate, inspire, collaborate, and experiment to discover and learn [37,38]. This prior work directs our beliefs that the integration of cyber–physical technologies into learning activities, with opportunities for semi-structured play can promote children's engagement and learning.

Our research also draws on Human–Computer Interaction (HCI) studies on storytelling with tangible and digital tools that specifically highlight storytelling as a constructionist activity [39–42]. Examples include: PETS (Personal Electronic Teller of Stories) [43], a child-assembled, augmented toy that supports emotional expression as children create and tell stories. PETS provides children a robotic pet to express behaviors and emotions; however, does not offer a setting where multiple pets can perform collectively as different segments of one story. StoryMat [44] is a system designed to support children's collaborative storytelling. Children move around a blanket while they make stories with tangible

objects; however, no electronics are involved to provide instant feedback while children arrange toys on the mat. StoryRoom [45] and POGO [40] provide storytelling opportunities where children play with tangibles emitting visual and sound effects that guide the storytelling activity. These storytelling tools are valuable for learning, but differ from CyberPLAYce, as they do not provide the same degree or use of spatial elements for children to physically build story segments.

Collectively, this prior research suggests using tangibles where children program toys and robots to tell stories in real world settings, is a promising way to learn. These projects do not necessarily provide spatial construction tools, with embedded cyber–physical technologies, for children to build the story space while making stories. CyberPLAYce provides electronic panels and modules for children to creatively express themselves, to construct meaning spatially, and to communicate during playful learning activities.

Similarly, numerous educational, computer-based projects allow children to construct and customize virtual worlds within computers. For example, in "physics microworlds" [46], children have control over the movements of Newtonian "dynaturtles". In other computer-based programs, children can virtually construct and manipulate urban environments, houses, streets, and shops, and then mandate tax rates for the city [47]. CyberPLAYce provides an alternative to constructing and controlling worlds on computers, allowing children instead to construct worlds in reality wherein children engage with computation within their own personal, physical environments. For instance, a child might connect a small computer (microcontroller) to a door, therefore programming the computer to automatically turn on LEDs whenever someone enters the room, or program the computer to welcome visitors as they enter the room, or program the sound of a siren if an intruder enters the room overnight [17].

1.3. The importance of thinking computationally

There is a growing interest in honing CT for all students [48,49]. Computational thinking has been defined in different ways, but in general, CT is considered an approach to understanding and solving problems. More precisely, CT is about planning and designing systems by employing fundamental concepts in computer science [7,50]. Computational thinking has been contextualized as a range of skills useful for successful problem solving in various areas of STEM, not just computer science.

The CyberPLAYce research utilized Barr and Stephenson's [50] characterization of CT, using a professional practice cycle that includes *decomposition*, *pattern recognition*, *pattern abstraction,* and *algorithm design*. CyberPLAYce helps children break down a complex problem or task into smaller and more manageable parts (*decomposition*), which allows for noticing similarities and common difference that will help make predictions or lead to shortcuts (*pattern recognition*). Subsequently in the problem-solving process, unnecessary information will be removed, focusing on concepts relevant to understanding and solving problems and completing tasks (*pattern abstraction*). Lastly, children develop set of step-by-step instructions to complete the problem-solving process through creating an algorithmic solution (*algorithm design*) [7].

2. Methods

2.1. Prior usability studies and an introduction to Prototype B-1

The study reported here followed two usability studies with earlier CyberPLAYce prototypes, Prototypes A-1 and A-2 [51]. In the first of these earlier studies, a multidisciplinary design-research team (two architects, an education specialist, a computer scientist, a robotics engineer, and six interaction designers) developed a common framework for designing a tangible tool that would engage children in playful activity while enhancing their learning and storytelling experience. After debating the different aspects of the tool, including its physicality and its user experience, as well as connecting learning theory and digital media research, the team developed Prototype A-1 (Fig. 2, LEFT). The first CyberPLAYce prototype was comprised by the open-source Arduino microcontroller and software platform [52], hand-sized, magnetic modules integrating a variety of electronic components, and rectangular panels that receive the modules and serve as building blocks for constructing cyber–physical environments imagined by children. Additionally, CyberPLAYce includes non-electronic *icon cards* (Fig. 3, RIGHT) allowing children to quickly compose pattern sequences to map ideas, stories, and class content. The icon cards depict various concepts such as sound, light, distance, and temperature, which can be changed for different scenarios. The cards are matched to electronic modules, which can provide instant feedback to children during plug-and-play activities.

The main intent was to design a tool that allows children to pick from a series of cards based on a given problem or story, and physically (re)construct the story or the problem setting in order to brainstorm and solve the problem collaboratively.

An early test of CyberPLAYce Prototype A-1 was conducted with four 8–10 year-old children in a classroom setting. The intention was to create a scenario matched to various input–output activities linking cards, modules, and ideas while suggesting how CyberPLAYce might provide children the means to think, learn, and share through a multi-media, tangible experience. The preliminary study with Prototype A-1 was conducted during the concept-and-design stage, and informed the research team by demonstrating how children respond to several existing activities and routine tasks. The study led us to adapt CyberPLAYce activities into storytelling activities aiming to strengthen children's active engagement with the CyberPLAYce components. During a story-creation activity, we imagined that children would make a story in a way that expresses only the words and icons provided to them; however, to our surprise, the research team found that the children wanted to create elaborate stories whenever they were using CyberPLAYce.

From Prototype A-1 to Prototype A-2 (Fig. 2, RIGHT), we focused primarily on updating the Arduino code, strengthening magnetic joints between the large panels, and enhancing the visual appearance of CyberPLAYce based on children's feedback. The changes were minor and, the overall design remained the same.

From the initial study, we iterated the design of our cyber–physical tool in a manner allowing the child input and the system output to occur in the same artifact [53]. In contrast to many activities offered by digital storytelling tools, in our design, much of the child's experience and creation is present in the physical space, and there is an output for each plug-and-play activity. Active engagement becomes evident through the extra layer of interaction when children spread, exchange, or replace the story segments across the table without being tied to a piece of paper or a digital screen.

Our second pilot study of Prototype A-2 with the same participants indicated that lighter panels with more robust joints (connections) were required to enhance the development of children's tangible CT skills. Thus, feedback, observations, and usability studies guided the research team to ultimately design and develop its third, fully functioning prototype, Prototype B-1 (Fig. 3), employing more robust materials and design details. Although Prototype B-1 offered a better opportunity for improving children's spatial reasoning, in this study, the main focus was given to teaching CT practices to children through interactive storytelling activities.

To facilitate imaginative design activity and promote tangible affordances within the system, Prototype B-1 has triangular-shaped light panels that feature receiving (plug-in) modules and

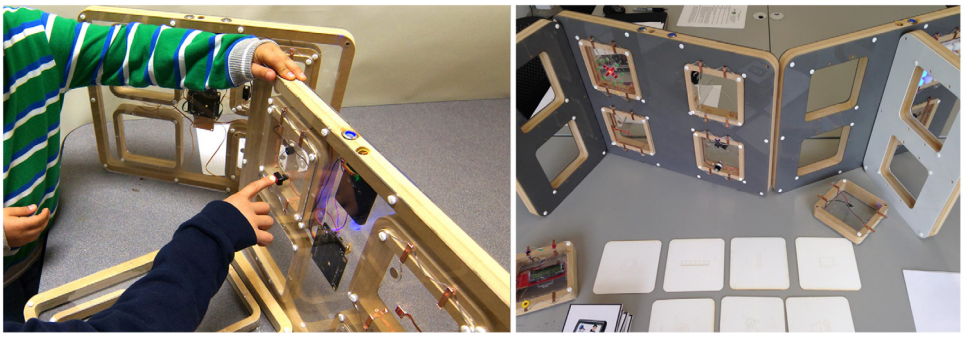


Fig. 2. CyberPLAYce Prototype A-1 (LEFT) and CyberPLAYce Prototype A-2 (RIGHT).

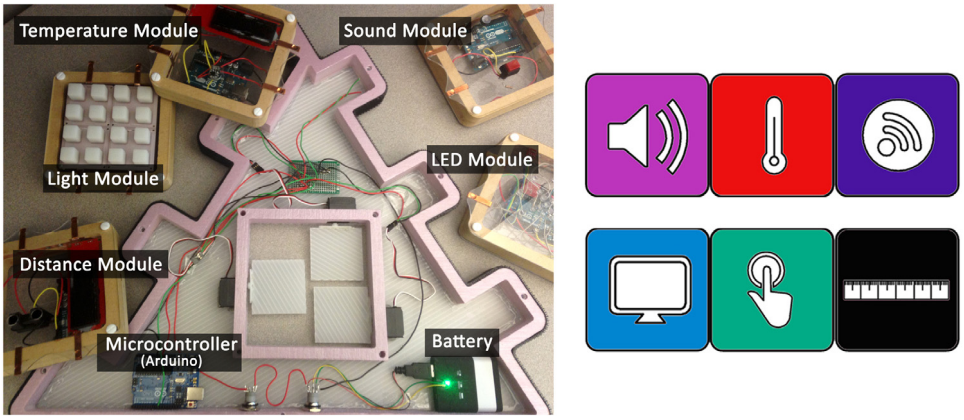


Fig. 3. CyberPLAYce modules (LEFT) and CyberPLAYce icon cards (RIGHT).

moving flaps (digitally controlled, motor-driven components). Additionally for Prototype B-1, a friction joint was designed and built using Velcro to establish temporary connections between the panels while improving the opportunity for children to construct large structures in the space with lightweight materials. Before elaborating our investigations with Prototype B-1, it is worth noting that the arc of the CyberPLAYce research, from its earliest activities to that reported here, exemplifies *Research-through-Design* [54] by which design processes are engaged in and communicated in a robust manner. *Research-through-Design* (RtD) is a research methodology that benefits from insights obtained through design practice in order to enhance the understanding of intricate and future oriented problems in the field of design [54]. In the arc of this RtD exemplar, the study of focus aimed to evaluate the high-fidelity Prototype B-1, and elicit data on the system's efficacy. Our specific research questions for this study were:
(1) How does CyberPLAYce Prototype B-1 support children's storytelling experience?
(2) How does CyberPLAYce Prototype B-1 enhance children's computational thinking through playful activities?

2.2. Context

The research was conducted at Hunter Middle School (pseudonym) over five days (1 session in the first week and 2 sessions in the second and third weeks, and 1.5 h per session). Located in the Southeastern United States, Hunter Middle School is a state-of-the-art public school featuring collaborative learning spaces, movable furniture, and one-to-one technology access. The school opened with 20 teachers, 2 administrators, and 365 sixth-grade students, with plans to add seventh and eighth grade students over two years. The curriculum focuses on increasing Science, Technology, Engineering, the Arts and Mathematics (STEAM).

2.3. Participants

Eleven 6th-grade students (11–12 years old) were randomly selected amongst thirty students (N = 11; six girls and five boys). Their classroom teacher suggested that the selected students represented a range of backgrounds and ability levels. The students then were divided into two groups: one group of five students (3 girls and 2 boys), and one group of six students (3 girls and 3 boys). Each day, students left the 'video production' class for 1.5 h to complete specific tasks in a different classroom.

2.4. Data collection

Data was gathered by the first author to gauge how the participants used CyberPLAYce Prototype B-1 during storytelling and story-creation activities, guided by established protocols for evaluating interactive technology for children [55], and to understand participants' CT activities. Collected data included video, audio, observations, and students' artifacts. Participants were audio/video recorded during every 90-minute session for five days, observations were conducted during each session, and surveys and questionnaires were administered on the second half of each session on day 2, 3, 4, and 5. For audio/video recording we set up two cameras in the classroom and placed an audio recorder on the table where students interacted with CyberPLAYce. A photographer was present during all the sessions. Lastly, all the written handouts and students' artifacts such as sketches were collected daily.

2.5. Data analysis

The collected data was analyzed in two ways, using a grounded theory approach [56]. First, we coded students' representation of

a given story with regards to Wing's [7] CT practices including *decomposition*, *pattern recognition, pattern abstraction*, and *algorithm design*. Second, the data was analyzed by making a comparison between story-construction and storytelling activities, with and without CyberPLAYce. This provided us a platform to measure how many details students remembered while retelling a given story, and how well the children interpreted and articulated the icons while using paper versus CyberPLAYce.

2.6. Process

In brief, here are the daily activities for this investigation; the sections below include greater details:

On Day 1: Demonstration and exploratory play with CyberPLAYce components

On Day 2: Group 1 participated in a retelling of Jane's story

On Day 3: Group 2 participated in a retelling of Jane's story

On Day 4: Group 1 participated in a global warming storytelling activity

On Day 5: Group 2 participated in a global warming storytelling activity

3. The study

3.1. Day 1: Learning about CyberPLAYce components

On Day 1, the first student engagement with Prototype B-1, all student participants were provided information and a demonstration of the different components of the CyberPLAYce construction kit. During the first half of the 1.5-h session, both groups of students interacted with the CyberPLAYce components, including its cards, modules, and panels. Students played with the components of CyberPLAYce to become comfortable with them. During the second half of the session, each group was provided six panels, 2–3 modules and icon cards, a pen, and scratch papers. The students were asked to collaboratively find and match some daily routine tasks with the provided cards and modules. The students then arranged the CyberPLAYce components in a specific order to create a story of their interest. One student from each group took the responsibility of handwriting the created story. Below are the stories from the two groups of students representing the specific order of the cards created by each group:

Group 1: *Joe is on an airplane. The plane suddenly sends out a loud screech, and lights start flashing from green to red. A spiraling wind whirls outside. The people's screams are muffled by the sound coming from the wind. Then, the plane rushes downward, and Joe plummets slowly into the icy water of the Atlantic Ocean. . ..*

Group 2: *Jack was going home till he saw a rainbow sign in a mysterious room. He entered the room. The room was too hot. He just had to connect a piece of wire to the other wire to make the rainbow light. After he connected it, some panels started spinning. Then the panels made the room temperature cooler. . .*

At the end of the first session each group represented their story to the class through a combination of CyberPLAYce components. For example, Group 1 used three panels of CyberPLAYce to make a pyramid-shaped structure in order to reconstruct the moment of the plane crash. Additionally, they used the sound, temperature, and distance, modules to communicate their story segments through a plug-and-play activity via the CyberPLAYce modules and panels. Group 2 used six panels to make a box representing the "mysterious room" in the story. They then used light, sound, temperature, and distance modules, plugging them into the panels ("walls" in this story) while representing various mysterious features about the room in accordance to the storyline. For the day-one task, students explored on their own while interacting with the CyberPLAYce components and making their own stories.

Finally, each individual student was asked about the functionality of the cards, modules, and panels to assure that all the participants knew how to use the various components.

3.2. Days 2 and 3: Storytelling activities through CyberPLAYce

Jane's story. On Days 2 and 3, only one group of students participated in a 1.5-h session each day (group 1 attended on Day 2, and group 2 on Day 3). The students were provided with a problem statement:

Sometimes, what matters most are the order of events and remembering things in detail. In math, the order of operations is important when solving an equation. In career task, like police work, or taking an order at a restaurant, or making food, what matters are the directions, the order in which you do things, and the details required for doing things.

The students were asked to think about their morning routine tasks very carefully and retell each step of the routine, from waking up until leaving the house. After brainstorming, all six participants listened to 'Jane's story', played through a laptop:

The sun rises just before Jane's alarm goes off. When Jane hears the sound of the alarm, she pushes a button to turn it off. She turns on her bedroom light and her room becomes yellow. Jane walks to the bathroom to take a shower, but first she tests the water to make sure it isn't too hot. After Jane showers, she runs back to her room to turn the light off. Jane sees a rainbow outside her window. On the way out of her bedroom, Jane accidentally slams the door. . ..

Each student was provided a copy of Jane's story and a colored highlighter to identify story segments according to the icon cards, aligned with CT practices (i.e., the *decomposition* process). The students individually highlighted and numbered story segments in the order of the storyline (see Fig. 4).

The participants then found the unnecessary icon cards not used in Jane's story (emulating the *pattern abstraction* process). Each student drew a diagram to illustrate the order of the story through the associated icons (the *algorithm design* process). Lastly, all the students compared their findings with each other, and a group member transcribed the group's findings on a single page according to the students' discussion of the story segments (see Fig. 5).

Next, each group was provided a handout offering empty boxes for the participants to enter the list of input/output activities (story segments) with the associated icons. Fig. 6 shows how each group collectively organized the story segments, matched with the icon cards and following the storyline.

Group 1 was asked to retell Jane's story, first through the algorithm that the students developed on paper, and then as retold through CyberPLAYce modules and panels (see Fig. 7). Group 2 reconstructed Jane's story through CyberPLAYce components first and then through the created algorithm. This activity provided a platform to compare students' knowledge attainment of CT practices while using pen and paper versus using CyberPLAYce components. To help minimize threats to validity by preventing any pre-knowledge attainment by the students, we employed a counterbalanced design where one group retold the story using their written notes, first, and then used CyberPLAYce to reconstruct and retell the story, while the other group reconstructed and retold

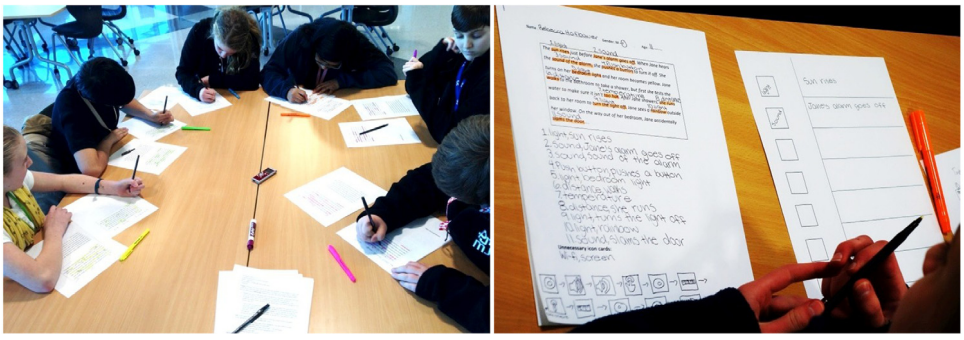


Fig. 4. Children identifying Jane's story segments and matching with icon cards.

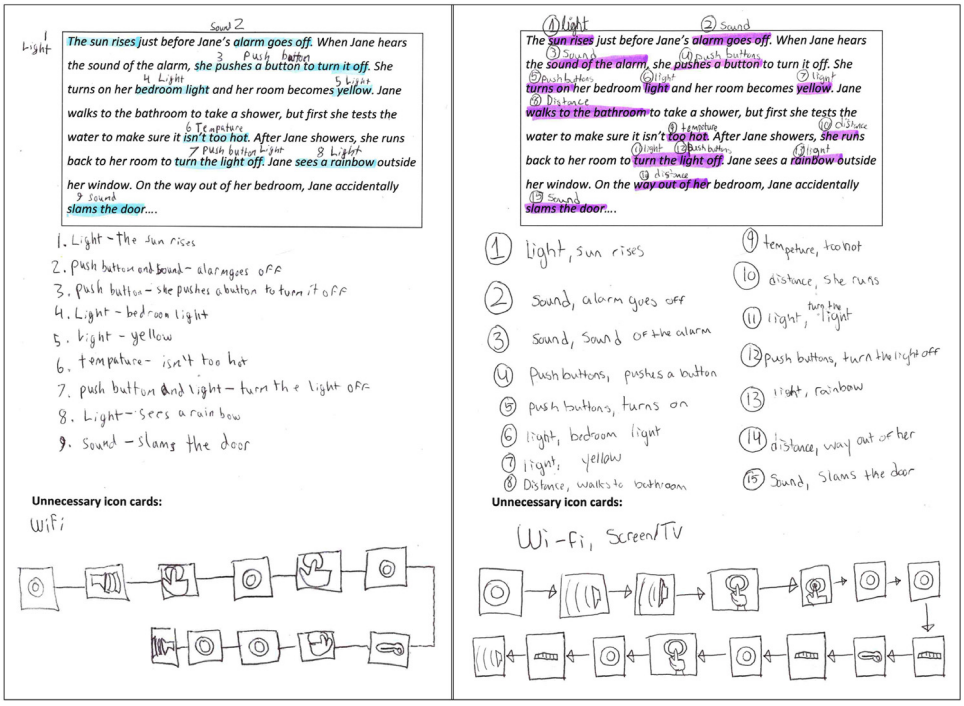


Fig. 5. Two groups' process of computational thinking practices for Jane's story, (LEFT: Group 1, RIGHT: Group 2).

the story using CyberPLAYce, first, and then retold the story using the written notes.

The eleven students also individually completed three activities aligned with CT practices, which included *decomposition*, *pattern recognition,* and *pattern abstraction*. Subsequently, the students in each group discussed their findings with each other and collectively performed all the four CT practices (i.e., *decomposition*, *pattern recognition*, *pattern abstraction,* and *algorithm design*) as a group activity. To determine if evidence existed in regards to the student's ability to decompose the story, they were provided handouts, which included Jane's story. The students had to identify and highlight story segments using the colored highlighters provided to them. The pattern recognition process was determined when the children matched their findings (story segments) to the icons cards. The students' ability to remove the unnecessary icon cards (here, the Wi-Fi and Screen cards) demonstrated the pattern abstraction process.

The algorithm design process was achieved when each group of students developed a flowchart of the icons representing each story segments that they found through the decomposition process (see Fig. 5: BOTTOM).

3.3. Days 4 and 5: Story-creation and storytelling activities through CyberPLAYce

Global warming scenario. Research on Days 4 and 5 focused on a global warming scenario. Each day, one group of students worked with us to learn about potential causes of global warming and considered how to construct solutions to slow-down or prevent global warming. Initially, we questioned students regarding their understanding of the global warming phenomenon and encouraged them to discuss this urgent issue with their peers; subsequently, they were provided an overall description about global warming:

> *Most scientists believe that global warming has a daily impact on the earth. Global warming is defined as a gradual increase in the overall temperature of the earth's atmosphere. If we continue with "business as usual", half of the species that exist today will be extinct by 2100 – in a mere eighty-five years. Global warming causes climate change, and climate change can cause water and food shortages, violent weather events like tornadoes, tsunamis and hurricanes. Ninety-seven percent of scientists argue that most of our global warming problems are caused by humans and could be prevented by humans.*

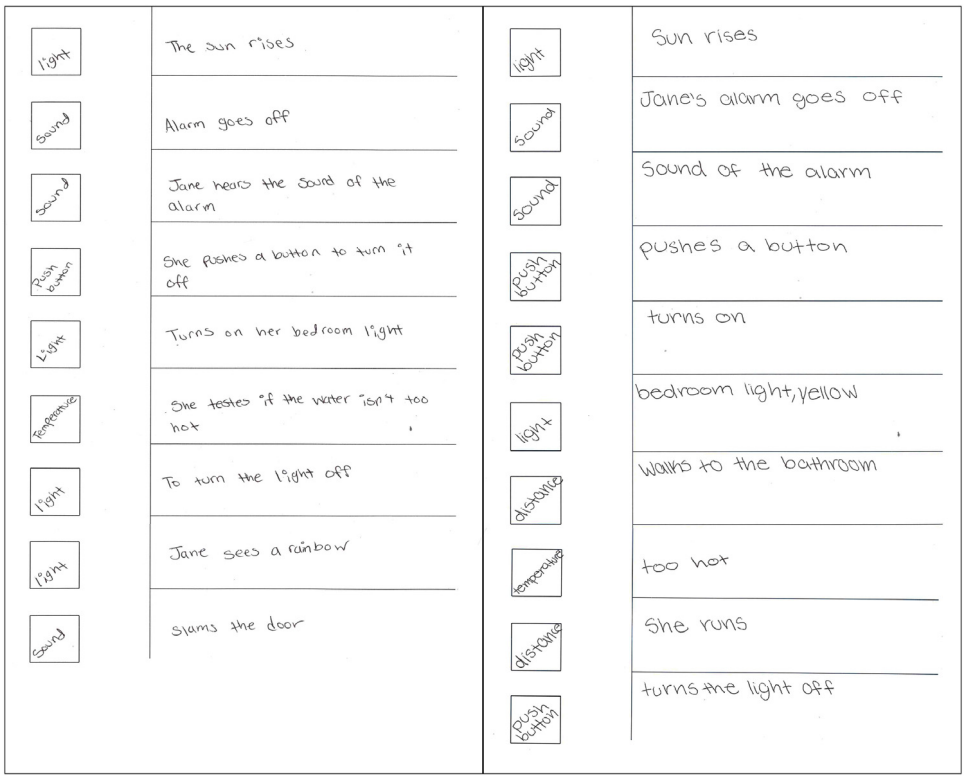


Fig. 6. Matching story segments with the icon cards, (LEFT: Group 1, RIGHT: Group 2).



Fig. 7. Group 1 engaged in the Jane's cyber–physical storytelling activity.

After discussion, the students were provided blank sheets of paper to write solutions to global warming while discussing potential solutions with their peers. They were asked to find some possible ways that global warming might be prevented and suggest activities that might conserve energy, thereby reducing global warming. To complete the brainstorming process on different potential solutions to global warming, the research team provided students with several specific examples of activities that can slow-down global warming. Each activity was related to a specific CyberPLAYce icon card.

(a) Light (*change light bulbs to LED lights and turn extra lights off*)
(b) Temperature (*wash cloths in cold water and adjust the thermostat*)
(c) Sound (*spread the word to educate friends and family*)
(d) Distance (*use public transportation, ride bicycles, and use fuel efficient cars*)
(e) Flaps (*use wind turbines to generate clean energy, and use natural wind for air-conditioning*)
(f) Display (*install electricity monitors and use shower controllers*)

After assuring that the participating students reasonably understood the global warming issue and possible solutions (through questioning), each student was asked to match their solutions to the associated icon cards and write them on the handouts provided (Figs. 8 and 9). The students were then asked to combine two or more solutions together and find combined solutions to global warming. For example, one student picked the screen, sound, Internet, push button, and light icon cards representing an activity when someone makes a YouTube video to educate people on global warming: the push-button icon card was used to represent the act of turning-off extra lights and to represent a keyboard for making a video; the screen card was used to represent the video on the monitor; and the Internet card was used for disseminating the video on the Internet for the purpose of educating people on how to slow down global warming.

Lastly, in each group, one student was asked to collect and communicate all the students' solutions on one sheet. All of the participants discussed the solutions; and then, together, they found at least three "combined solutions" (see Figs. 8 and 9). Subsequently, each group constructed a story using the combined solutions to convince people of what they might do to prevent global warming.

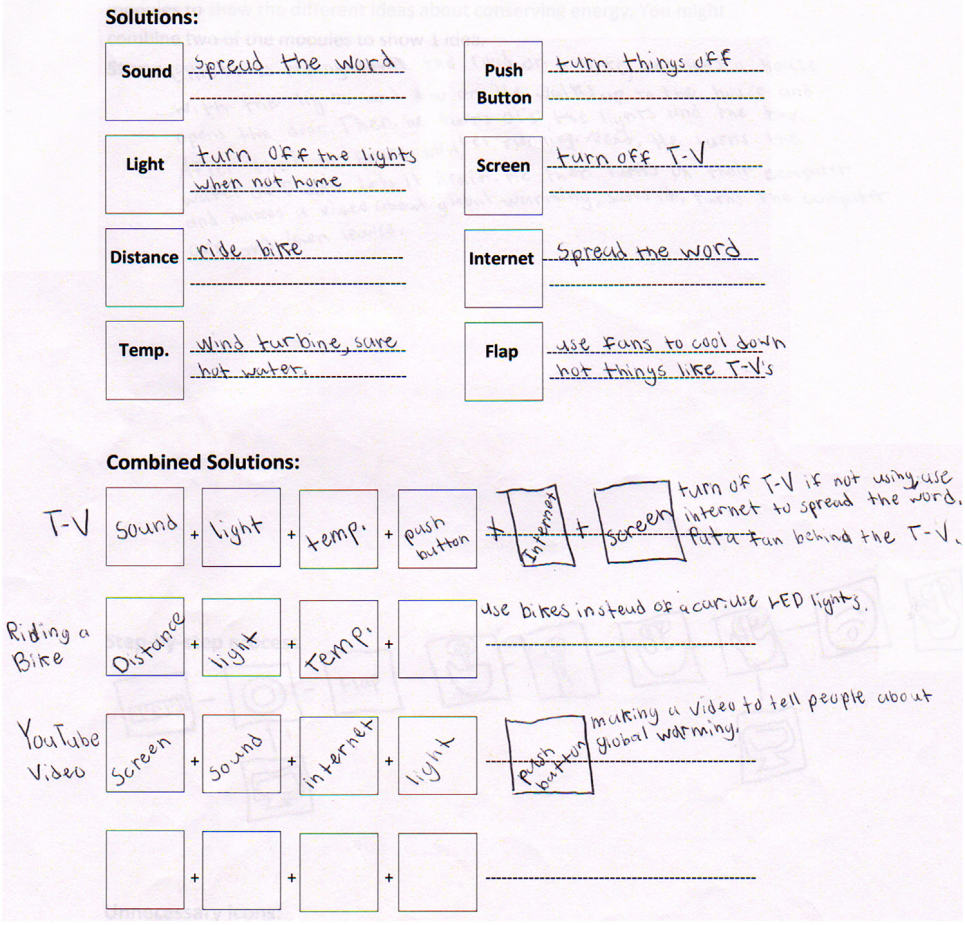


Fig. 8. Group 1's proposed *solutions* and *combined solutions* to address the global warming issue.

The participants had the chance to choose any of the icons, to decide not to use some of the icons (i.e., *pattern abstraction*), or to use the same icon more than once (i.e., *pattern recognition* and *pattern generalization*). Afterwards, each group developed an algorithm of the icons representing their storyline. The students used the algorithm to present their story to the research team through a verbal expression of the story algorithm first; and then second, through the CyberPLAYce modules and panels. This provided the research team a platform to compare the students' storytelling activity through the multimodal CyberPLAYce components as compared to the sole verbal representation of the story.

Each group of students constructed a story based on the combined solutions that they created earlier. Group 1 created the following story based on three combined solutions i.e., *Television*, *Riding a Bike*, and *YouTube Video*:

> *Elliott is riding down the road on a bike and sees a house with the lights and TV on. He walks up to the house and opens the door. Then, he turns off the lights and the TV. After that, he hears water running. Next, he turns the water off and lets it drain. He then turns on their computer and makes a YouTube video about global warming, saves it, uploads it, turns the computer off, and then leaves.*

Group 2 created the following story based on four combined solutions including *Television*, *Riding a Bike*, *Internet*, and *Chimney*.

> *There was a man named Nortan. He woke up and turned on the news, and forgot to turn it off. His job was in a factory, and they built teddy bears. The fumes from the teddy bears went in to the air. As he walked outside for his lunch break, the pouliton [pollution] police show up and come up to Nortan and said "sir, you are in trouble, because you did not turn off your TV, lights, sink, and the engine. When you turn off those things, you save a polar bear. PLEASE TURN OFF YOUR THINGS".*

4. Results

We discuss the results of our study as related to each research question; in our evaluation, we acknowledge the overlap between students' storytelling activities and CT practices with CyberPLAYce.

4.1. CyberPLAYce fosters children's storytelling experience and active engagement (RQ 1)

By designing CyberPLAYce, we aimed to create a tool that can be easily tailored by children and teachers, and that can be easily re-configured in the space to suit different tasks, topics, and physical settings. The tangible interaction is important in this context because it enhances children's collaborative activities while exchanging and communicating through the physical objects. During CyberPLAYce activities, when students told their story from the written paper (traditional storytelling), they did not think about any alterations or interactions between the story segments to make the story more sophisticated and informative towards educating the audience about global warming. In other words, the students did not think about the spatial interactions between the *combined solutions* and the story context. Each group verbally expressed the story with no further discussions between the group members; however, the body of the story was changed several times (three times for Group 1 and twice for Group 2) when the

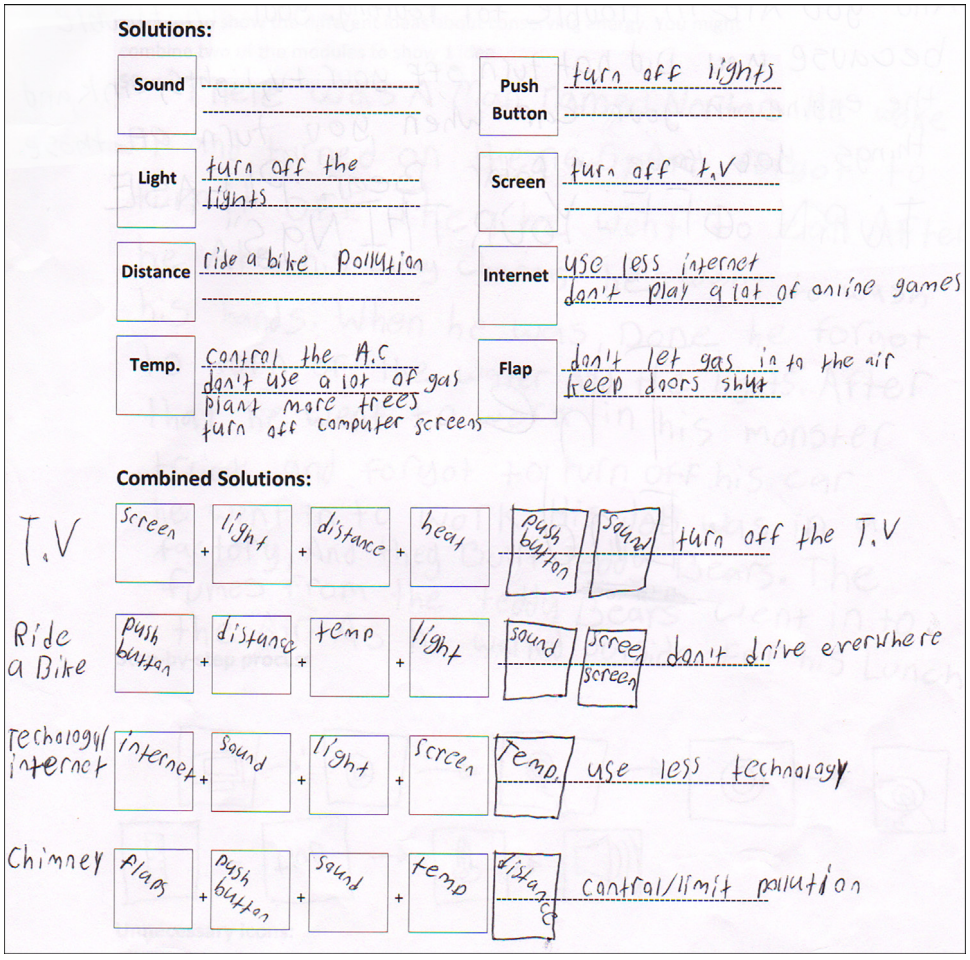


Fig. 9. Group 2's proposed *solutions* and *combined solutions* to address the global warming issue.

children were constructing the story segments spatially through the CyberPLAYce modules and components (Fig. 10). This suggests that CyberPLAYce as an interactive learning tool encourages children's active engagement through the storytelling experience better than the traditional way of telling stories.

CyberPLAYce addresses Kafai's [17] ideas regarding the positive influence of a tool towards a learning activity. In this case, using the tool allowed students to be experts when constructing their stories and constructing new knowledge, and they found the activity fun and motivating as evidenced by observations and post-survey data. We provide examples that typify students' response towards CyberPLAYce and the storytelling activity which further illuminate how the activity assisted in their knowledge construction and portrayal.

CyberPLAYce supported children's storytelling experience in two primary ways. First it allowed them to imagine and spatialize narratives in a way that traditional storytelling did not, and second it increased their engagement in collaborative storytelling producing sophisticated, complex stories. Below we explain how CyberPLAYce enhanced children's 'spatial organization' and 'collaboration and active engagement' during the activities.

Spatial Organization. CyberPLAYce helped children make sense of the story segments and given problems by physically constructing story algorithms (see Table 1, A). This also allowed children to make connections between the CyberPLAYce components and real life experiences (see Table 1, B). For example, one student from Group 1 suggested to the other students that they make the entire story with panels like a house with walls, containing push buttons to turn the lights on and off. After connecting the panels in the order of the storyline, the students began to think about directions: *From which direction is Elliott approaching the house when he is riding his bike in the neighborhood? Where should we put the windows so that Elliott can see through them?* One student had the idea to bring the "water loss" (a story segment) to the beginning of the story where Elliott is riding his bike and unexpectedly gets wet by the water sprinkler set in a neighbor's garden. This draws Elliot's attention to turn the sprinkler off, and to enter the neighbor's house to turn the extra lights off. The CyberPLAYce panels and modules helped students to physically construct the story algorithm while affording them the opportunity to reorganize or otherwise alter the story segments when connecting the panels and telling the story simultaneously (see Fig. 10; see Table 1, D).

Collaboration and Active Engagement. At the same time, CyberPLAYce provided several collaborative situations for students to communicate with each other whether during the story-construction or storytelling activities. The given tasks required children to complete series of individual and group tasks. Furthermore, the CyberPLAYce tool itself, as a shared artifact, encouraged students to collaborate during the activities. This was especially evidenced, when children where constructing and reconstructing stories based on each other's feedback.

Observation notes and survey instruments evidenced how students expressed their engagement with CyberPLAYce as they discussed the value of constructing stories with the tool. One student mentioned, "*I like using the panels because you have to think more, and it is fun!*" Another student said, "*when I build a story [with CyberPLAYce], it helps me remember it more easier, but when it is on*

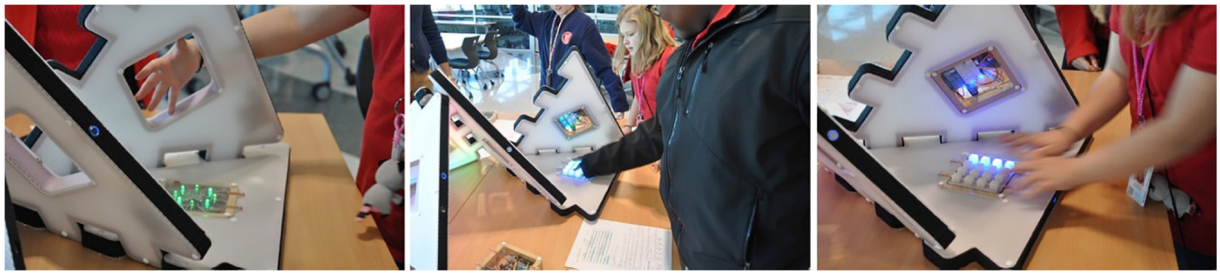


Fig. 10. Children engaged with the global warming scenario.

Table 1
Categories of CyberPLAYce practices enhancing children's active engagement, storytelling, and story-creation experiences with examples from participating children.

A	*Children make sense of the given story/problem*	
	While explaining the solutions for *Global Warming Scenario*, one participant said:	"Global warming is difficult and hard to see, but CyberPLAYce made it easy to see all the solutions in one place".
B	*Children make connections between the CyberPLAYce components and real life experiences*	
	In response to CyberPLAYce spatializing the story in *Global Warming Scenario*, one group said:	"Let's make the entire story with panels like a house with walls, containing push buttons to turn the lights on and off".
C	*Children remember story segments*	
	While telling *Jane's story* through CyberPLAYce after spatially constructing story segments, one participant said:	"When I build a story [with CyberPLAYce], it helps me remember it more easier, but when it is on paper, I didn't seem to remember it any easier than the panels".
D	*Children reorganize story segments and explore different solutions to solve the given problem*	
	While making the story for *Global Warming Scenario* and using CyberPLAYce components, one participant said:	"We should reorganize the story segments around the house to find the right direction when Elliot approaching the house".
E	*Children elaborate on the story*	
	While explaining her rationale for selecting panels with moveable flaps in *Global Warming Scenario*, one participant said:	"When the flaps move, it makes it like wind turbines which can generate clean energy and slow down global warming".

paper, I didn't seem to remember it any easier than the panels". (see Table 1, C) The tangible component of CyberPLAYce was engraining and encouraging to students in terms of creating and telling stories. One participant mentioned, "*to me, building something to explain a story makes the experience more memorable.*" Another student noted, "*The panels help you actually see and build the story better. It gives you a better visual*". (see Table 1, C) Eight of the students expressed a positive reaction to the visual–spatial aspect of CyberPLAYce; they loved how the story segments, associated with CyberPLAYce components, could be replaced, changed, or further developed at any time, with no limitations. During the storytelling and story-creation activities, the students were concerned with the physical location, orientation, and order of the CyberPLAYce panels and modules. This is in alignment with the CyberPLAYce hypothesis, which puts an emphasis on the importance of employing tangible learning tools in order to enhance children's active engagement and storytelling experience.

4.2. CyberPLAYce fosters children's CT practices (RQ2)

The observations and student artifacts suggest that the participating children's active engagement with CyberPLAYce components assisted in learning CT practices.

4.2.1. Jane's story

A comparison of the CT practices of the two groups indicated that Group 1 could correctly decompose 60% (9 of 15 story segments) of Jane's story while Group 2 decomposed all fifteen segments (see Tables 2 and 3). Both of the groups correctly recognized four patterns (icons) out of five existing patterns in the story, including the sound, distance, push button, light, and temperature icons. Furthermore, Group 2 found the two unnecessary icon cards featuring the screen and Wi-Fi icons, which were not used in Jane's story; however, Group 1 could only recognize the Wi-Fi card as an unnecessary component. Subsequently, each group of students collectively developed a linear and non-linear (tangible) story-algorithm (Figs. 11 and 12) in accordance with CT practices. Group 1 retold Jane's story through the linear algorithm (created on paper), first, and then through a non-linear algorithm that was constructed using CyberPLAYce panels and modules; Group 2 told the story through CyberPLAYce, first, and then used paper and pencil to retell Jane's story.

Although the participants spent more time constructing non-linear algorithms through the CyberPLAYce panels and modules, compared to when they used paper and pencil to create linear algorithms, both groups of students found it unnecessary to check each component of the algorithm (created on paper, as shown in the left half of Figs. 11 and 12) with the original, written story to remember the story segments that they listened to at the beginning of the study. However, when the students did not construct the story with the CyberPLAYce components, they were observed referring back to the original story to remember what the *light* icon refers to; this was because the *light* icon was used five times in the process of the *algorithm design* (Group 1 referred back to the main story once, while Group 2 looked for the original story segments twice). This observation suggests that the physical construction of the story algorithm, in an abstract way, helps children understand and remember story segments better than telling a story from paper.

4.2.2. Global warming

During Days 4 and 5 of the study, 11 students individually completed the CT practices of *pattern recognition* (solutions) and *pattern generalization* (combined solutions). Subsequently, the students of each group discussed their findings with each other, and they collectively performed three CT practices (*pattern recognition*, *pattern generalization*, and *algorithm design*) as a group activity. Students' capability of recognizing patterns was evidenced by their ability to seek solutions to the global warming issue and match them to the relevant icons on the provided handouts, including icons for sound, light, distance, temperature, push button, screen,

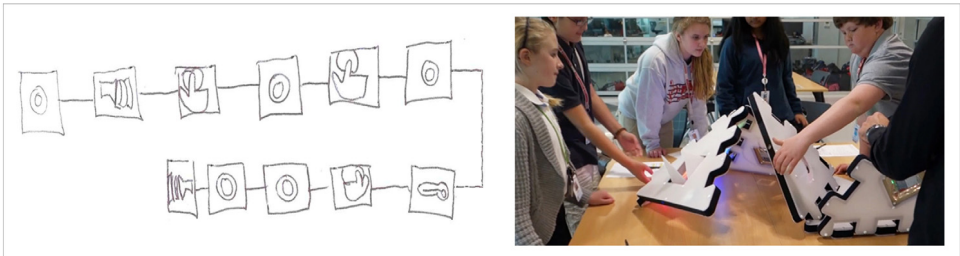


Fig. 11. Group 1's constructed linear (LEFT) and non-linear (RIGHT) story algorithms for Jane's story.

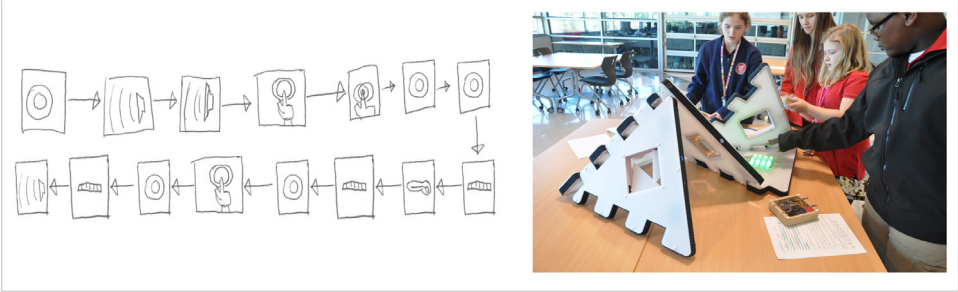


Fig. 12. Group 2's constructed linear (LEFT) and non-linear (RIGHT) story algorithms for Jane's story.

Table 2
Group 1's computational thinking practices—Jane's story.

CT practices	Students ($N_T = 6$)[a]	Decomposition (total = 14)[b]	Pattern recognition (total = 5)[c]	Pattern abstraction (total = 2)[d]
Individual activity	S_1	9	3	1
	S_2	9	4	1
	S_3	6	3	1
	S_4	8	3	1
	S_5	9	3	1
	S_6	9	4	1
Group activity	Group 1	9	4	1

[a]Total number of students (Group 1) attended day 2 of the CyberPLAYce study.
[b]Total number of story segments in Jane's story including (1) sun rises, (2) alarm goes off, (3) sound of the alarm, (4,5) pushes a button, (6) turns on, (7) bedroom light, (8) walks to the bathroom, (9) too hot, (10) she runes, (11) turn the light off, (12) sees a rainbow, (13) way out of her bedroom, (14) slams the door.
[c]Total number of icon cards involved in Jane's story including sound, temperature, light, push button and distance cards.
[d]Total number of unnecessary cards that were not used in Jane's story including Wi-Fi and screen cards.

Table 3
Group 2's computational thinking practices—Jane's story.

CT practices	Students ($N_T = 5$)[a]	Decomposition (total = 14)[b]	Pattern recognition (total = 5)[c]	Pattern abstraction (total = 2)[d]
Individual activity	S_1	11	4	1
	S_2	14	5	2
	S_3	11	3	2
	S_4	8	3	2
	S_5	8	2	2
Group activity	Group 2	14	4	2

[a]Total number of students (Group 2) attended day 3 of the CyberPLAYce study.
[b]Total number of story segments in Jane's story including (1) sun rises, (2) alarm goes off, (3) sound of the alarm, (4,5) pushes a button, (6) turns on, (7) bedroom light, (8) walks to the bathroom, (9) too hot, (10) she runes, (11) turn the light off, (12) sees a rainbow, (13) way out of her bedroom, (14) slams the door.
[c]Total number of icon cards involved in Jane's story including sound, temperature, light, push button and distance cards.
[d]Total number of unnecessary cards that were not used in Jane's story including Wi-Fi and screen cards.

internet, and flap (Figs. 8 and 9: TOP). The pattern generalization process was determined when the students combined more than two solutions (icons) to create a combined solution to slow-down global warming (Figs. 8 and 9: BOTTOM). The algorithm design process was evidenced when each group of students developed a story with the combined solutions and designed a flowchart of the icons representing their solutions to global warming within a story format.

A comparison of the two groups' CT practices indicates that Group 1 found a solution for each of the eight provided icons; Group 2 could find seven solutions matched to seven icons out of the eight provided icons (that is, all the icons except for the sound icon) (see Tables 4 and 5). Group 1 generated three *combined solutions* while Group 2 created four *combined solutions* as the key segments to develop stories. This suggests that the use of CyberPLAYce assisted children in algorithmically developing solutions to complex problems using a step-by-step process. It also provides a platform for teachers to consider ways to assess students' computational thinking practices in various subject matters.

5. Discussion

In designing CyberPLAYce, we aimed to create a cyber–physical tool to support new modes of thinking, exploring, interacting, and sharing. We considered various types of interaction (physical, digital, and/or spatial), and gauged how these different modalities might enhance the personal, social, and computational development of young children. CyberPLAYce represents our novel effort to expand cyber-learning to the dimension of space while nurturing young learners' computational thinking capacities. Using CyberPLAYce supports Gee's [30] perspectives towards the educative value of play, allowing students to 'muck around' with the modules, panels, and electronics as they construct knowledge. In this study, students repeatedly tried out various possibilities, often collaboratively, and connected their solutions to what was familiar to them using their knowledge and the tool as scaffolds [6]. In this way, we see the value and possibilities of offering CyberPLAYce within semi-structured play activities to teach computational thinking, explore content, and foster interest-based learning and creative expression.

Table 4
Group 1's computational thinking practices—Global warming scenario.

CT practices	Students ($N_T = 6$)[a]	Pattern recognition (Solutions)[b]	Pattern generalization (Combined solutions)[c]
Individual activity	S_1	5 (8)	2
	S_2	5 (8)	1
	S_3	3 (8)	1
	S_4	5 (8)	0
	S_5	3 (8)	0
	S_6	6 (8)	1
Group activity	Group 1	8 (8)	3

[a]Total number of students (Group 1) attended day 4 of the CyberPLAYce study.
[b]The number of solutions to the global warming issue that students matched to the given icons including sound, light, distance, temperature, push button, screen, Internet, and flap icons.
[c]The number of combined solutions that students created through the combination of simple solutions that they created earlier.

Table 5
Group 2's computational thinking practices—Global warming scenario.

CT practices	Students ($N_T = 6$)[a]	Pattern recognition (Solutions)[b]	Pattern generalization (Combined solutions)[c]
Individual activity	S_1	4 (8)	4
	S_2	6 (8)	3
	S_3	4 (8)	1
	S_4	2 (8)	0
	S_5	3 (8)	3
Group activity	Group 2	7 (8)	4

[a]Total number of students (Group 2) attended day 5 of the CyberPLAYce study.
[b]The number of solutions to the global warming issue that students matched to the given icons including sound, light, distance, temperature, push button, screen, Internet, and flap icons.
[c]The number of combined solutions that students created through the combination of simple solutions that they created earlier.

5.1. Enhancing storytelling and computational thinking

Our research demonstrates that the tangible algorithm that children constructed through the modules and panels of CyberPLAYce offered them a tool to think algorithmically and enhance their stories through physical alterations to the panels and modules as the story segments. It also allowed students to express themselves by drawing on their interest in learning with cyber–physical tools and creating content that they cared about such as storylines that they choose to construct based on familiar experiences. This has been emphasized by learning science researchers as a valuable way to learn [24,25,28]. Similar to Moher's [33] embedded phenomena research, CyberPLAYce offers a situated, contextualized way to encounter phenomena by using physical space and tangible objects (in this case the CyberPLAYce tool) to simulate activities. While CyberPLAYce clearly offers more technologically sophisticated, 3-dimensional ways of interacting than the tools and objects used within Moher's studies, in both physicality played a significant role in fostering creative expression and learning. For example, when children used CyberPLAYce, they were concerned with the physicality of the whole story along with considerations of directions, orientations, shapes, and movements. The tangible algorithm created through the modules and panels of CyberPLAYce provided children a tool to reorganize the story segments, generalize the concepts and patterns, and use them in different ways, which was not available to the children when they narrated the story using pen and paper. With Jane's story, children learned how to decompose a complex task into smaller segments. In the global warming scenario, children learned how to create and perform complex tasks dealing with large-scale problems. Both activities were designed to augment children's CT capacities with regards to the CT practices of *decomposition*, *pattern recognition*, *pattern generalization*, *pattern abstraction*, and *algorithm design*. Participating children also used different approaches to make their own story, or to retell an existing story. Most children browsed the cards, modules, and panels of CyberPLAYce, and selected their own elements of communication. They learned how to interact with CyberPLAYce's components by decomposing Jane's story and matching the story segments to the cards and modules; they were then given key words to construct their own stories. Although CyberPLAYce differs in the types of tangible technologies used in prior research, such as electronically augmented physical artifacts which trigger events [34] or 2-D drawing tools and sensor-controlled "magic carpets" [35], our research is aligned with findings from these earlier studies and it confirms how engaging technologies can assist students in creating solutions and retelling stories in collaborative, imaginative ways. Furthermore, CyberPLAYce extends the capacity of tangible tools such as PETS, StoryMat, StoryRoom, and Pogo with its ability to iteratively design and spatially manipulate the elements of storytelling.

During the activities, the research team also observed several unexpected results when children were building their story through the panels of CyberPLAYce. The friction joints on the panels allowed the children to reshape the whole structure by pulling and pushing a panel without disassembling the structure. Hence, children experienced various spatial configurations of the CyberPLAYce tool while learning basic steps of engineering and architecture. This also helped children discover how their stories can be changed in different, imaginative ways. In general, our results indicate that CyberPLAYce offers a pathway aligned with Kafai's [17] viewpoint that a tool or language communicates the potential of a learning activity. Finally, similar to recent studies on productive play, it offered the students' meaningful contexts to test, view, and share their work with peers [36].

Overall, CyberPLAYce proved interesting, fun, and motivating; it portrayed knowledge in social, physical, and multimodal ways; it allowed children to be experts; it offered insight into how knowledge was constructed; and, based on largely positive responses from participants, it connected children with their abilities.

5.2. Potential to assess computational thinking

Educators as well as researchers are challenged by the lack of widely accessible and validated approaches to assessing CT [57]. Assessment strategies tend to be specific to a CT project and do not use an innovative tool like CyberPLAYce. For example, Grover and Pea point to a need for CT assessment strategies incorporating relevant tasks and activities in physical and digital environments. The CyberPLAYce team argues that the use of cyber–physical environments for CT assessment may provide improved understanding of how learners apply CT in more realistic situations than a paper and pencil test or computerized test.

The focus of our research was to build a cyber–physical learning tool that helps children think computationally, which involves decomposing a problem, recognizing and generalizing patterns, and developing a step-by-step instruction through a playful learning activity. This focus allowed for our investigation of the CT practices. During this study we gave children printed handouts offering Jane's story. Children initially used colored highlighters to mark-up different segments of the story (*decomposition*); they afterwards matched the story segments to the cards and modules (*pattern recognition*); they then followed with the removal of unnecessary cards/modules (*pattern abstraction*), and finally they diagramed the process of the story through a combination of cards, modules, and panels (*algorithm design*). The whole process helped our team

examine children's CT practices, focused particularly on how the young learners logically organize and analyze data while dealing with real-world problems.

Notably, CyberPLAYce is not designed only for a specific storytelling activity; it can operate with different scenarios. Children may reconstruct a given story or create their own story during the CyberPLAYce activities. In future investigations, our team imagines additional modules and cards that support children in the construction of stories in creative and expressive ways; and certainly, children will be provided tools to develop and customize their own cards, modules, and panels.

6. Limitations

As with any study, there are limitations to our findings. While children who participated in our study were diverse in terms of ethnicity and literacy levels, the small sample size and participant pool limits, to some extent, the generalizability of the findings. Nevertheless, as our intention was to explore a cyber–physical learning process – not merely conduct an evaluative study – the participation of children yielded invaluable input regarding the learning potential of CyberPLAYce. During CyberPLAYce activities, one thing that was observed several times was the lack of the option for children to customize panels, electronics, and input/output effects. Children often asked, especially when making their own stories, to change the color and/or brightness of embedded lights. They also asked if there are possibilities of changing sound loudness or playing different sound effects in accordance with the story segments. Overall, *customizability* is one of the major limitations of the current design, which is being considered for improvement in next iterations. One of the other limitations we faced during the study was establishing a concrete evaluation process to assess children's spatial reasoning. While we designed the CyberPLAYce tool and evaluative activities with regard to CT practices, later on in our study we noticed that the tool has an extensive capacity to improve children's spatial reasoning and thus plan to consider it in future iterations.

We recognize students in traditional classroom settings (versus our study's STEAM school setting) might respond differently. However, this limitation is likely a minor one as the study was completed early in the first year of the newly opened school. Finally, schools and learning methods are bounded by rules, and often limited to books; a condition that makes cyber, physical, and spatial dimensions of thinking and exploration challenging to reproduce across settings. However, our findings are promising in terms of offering strategies for the design and evaluation of novel tangible learning tools for children.

7. Conclusion

CyberPLAYce advances our understanding about how technology-embedded learning environments can support early learning skills in children. The research provides knowledge that could find application within a broad range of learning contexts by providing a new learning/teaching method for children and teachers. Schools recognize the critical importance of integrating emerging technologies into the learning environments. To this end, the CyberPLAYce research can provide schools with an innovative strategy that involves a fun, engaging, and effective learning experience for children, teachers, and parents.

This cyber–physical learning paradigm also offers a transdisciplinary approach to researching learning within educational systems. In this case, CyberPLAYce contributes to Computer Science, Education, and Architectural Design. At the same time, CyberPLAYce can be used inside and outside schools to teach different concepts with an emphasis on CT practices in different areas of science. Likewise, the physical and digital affordances within CyberPLAYce provide educators ways to teach preliminary concepts in such disciplines as architecture and computational design. Broadly, CyberPLAYce promises to help prepare young learners for the future demands of working and living in cyber–physical environments in our increasingly cyber–physical world.

Appendix

Link to a video demonstrating Prototype A-1 and Prototype B-1: https://youtu.be/r0uvqLFjWxA.

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