A Tangible, Story-Construction Process Employing Spatial, Computational-Thinking

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Abstract – The outcome of a multidisciplinary and iterative process, CyberPLAYce is a tangible, interactive, cyber-physical learning tool for children supporting computational thinking and, particularly, playful storytelling. CyberPLAYce finds inspiration in the concept of child-computer interaction, where meaning is constructed through spatially reconfiguring the physical environment. The novel aspect of CyberPLAYce is its extension of cyber-learning to the dimension of space where children construct meaning at a larger physical scale. This paper outlines the motivations for CyberPLAYce, focuses on the full arc of design and evaluation activities concerning computational thinking (CT) practices that engaged 8-12-year-old storytellers, and concludes with a consideration of future work focusing on spatial thinking with CyberPLAYce. Results from our empirical study suggest that cyber-physical play afforded by CyberPLAYce scaffolds computational thinking, creating, and sharing in children. Particularly for IDC researchers in the educational domain, CyberPLAYce represents a *Research-through-design* exemplar supporting children's enjoyment of learning and meaning-construction.

Keywords – Computer Support Tools; Play; Childhood Education; Storytelling; Interactive Environments; Architecture; User-Centered Design; Tangible Computing; Prototyping.

I. Introduction

As we come to live, work and play in an increasingly digital society, interactive system will inevitably be shaped by larger-scale, cyber-physical systems. CyberPLAYce (Figure 1) nurtures children's spatial and computational reasoning, both during and after CyberPLAYce activities, creating a multimodal experience that transforms real-world problems into playful activities. CyberPLAYce aims to bridge physical and digital worlds, allowing children to make knowledge tangible and spatial through hands-on manipulation of cyber-physical components.

This paper offers a scenario of the child-computer interaction afforded by CyberPLAYce, elucidates the motivations for its design, and focuses on evaluation activities and results.

Figure 1. CyberPLAYce (current prototype - B-1)
Children engaged in our cyber-physical storytelling study

A. *The Importance of Spatial Thinking*

Spatial thinking is the capacity to understand and remember the spatial relationships between objects, including both physical and digital elements, in order to solve different tasks. From routine tasks like riding a bicycle, to more complex activities such as building design or dealing with global-scale challenges like transportation system design, the way we explore and construct the space around us is important to solving problems. As Robin Tricoles asserts in *The Benefits of Spatial Thinking,* "for children, developing spatial thinking can determine the course of their career and perhaps their life, and for adults, it can mean the difference between mental clarity and cognitive decline" [33]. Nora Newcombe, an expert in cognitive development, argues that spatial thinking not only is useful in everyday life but also is beneficial in learning math and science [27]. She believes that spatial reasoning situates children on a fruitful trajectory [27]. For instance, block-play in children, a

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common childhood activity, can be the start of a developing interest and expertise in the fields of design and engineering. In the case of block-play, a child explores statics by attempting to build a structure as high as she can which, at its limits, tumbles over. The child then seeks the reason for the structural failure, and maybe responds by building a firmer base or stronger overall structure. These are initial steps to becoming a designer or an engineer.

Research also shows that spatial interactions with physical elements make for better learning, more broadly. For one, the Reggio philosophy reminds us that “the environment is a teacher” to children: that the physical environment in which children learn is central to fostering their capacities [30]. Learning arises in the interplay between bodily experience and conceptual insight [e.g. 28].

B. *The Importance of Computational Thinking*

There is a growing interest in computational thinking (CT) as a novel genre in education for students of all ages [5 & 14]. 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 [34 & 3]. Computational thinking has been contextualized as a range of skills useful for successful problem solving in various areas of the STEM, not just computer science. Increased attention to nurturing CT capacities across curricula by the Computer Science Teachers Association (CSTA) and the International Society for Technology in Education (ISTE) highlights its significance [8]. Computational thinking is viewed as a way to “magnify problem-solving skills needed to address authentic, real-world issues” in order to assist today’s students in meeting “workforce demands of the future” [8]. Moreover, CT promises “to help solve some of the most pressing, intractable problems of our time” [8]. CyberPLAYce employs Barr and Stephenson’s characterization of computational thinking [3] using a professional practice cycle that iterates (through decomposition of a problem) pattern recognition, pattern abstraction, and algorithm design.

II. MOTIVATIONS FOR CYBERPLAYCE

CyberPLAYce was designed as a 21st century *House of Cards* (Figure 2), created in 1953 by famed American designers Charles and Ray Eames. *House of Cards* is an oversized deck of playing cards featuring imaginative patterns and pictures on their surfaces that children join together to give form to their thoughts through spatial construction. Adding computation to this recipe, CyberPLAYce puts the emphasis on the process of design rather than only considering the final product. Applied to the problem solving and planning skills of early learners, this means that the design context can situate children in the mode of thinking like designers, problem solvers, and planners. By focusing on the design context, children as co-designers employ planning and problem solving while quite literally constructing knowledge and artifacts [31].

Figure 2. Children giving form to their thoughts and ideas through the spatial reconfiguring afforded by House of Cards (1953) (LEFT) and CyberPLAYce (first prototype) (RIGHT)

In concept, CyberPLAYce also builds upon the idea of embodied, child-computer interaction [10], where “meaning is constructed through restructuring the spatial configuration of digital-physical elements in the environment” [2]. With CyberPLAYce, “an object-to-think with” [29], children explore concepts through bodily, cyber-physical interaction. CyberPLAYce seeks to provide children a tool to systematically solve real-world problems and construct stories while nurturing their capacity to understand and remember the spatial relationships between cyber-physical elements in the space (i.e., spatial computational –thinking).

Research indicates that well-developed play has positive impacts on the development of children [20]. Indeed, the concept of play has been well-considered by the HCI community [13, 21, 24, 26]. By developing children’s personal and computational expression through spatial and computational thinking, CyberPLAYce aims to promote children’s active involvement and imagination in creating their own play activity. This aspiration aligns with Caillois’s paidia play [13, 21], where play is open and affords uncontrollable imagination while giving life to fantasy worlds using physical-digital elements (see, e.g., [1, 9]). CyberPLAYce takes inspiration from studies on storytelling in the field of HCI [9, 18] that specifically highlight storytelling as a creative activity: in PETS [11], child-assembled, augmented toys support emotional expression as children create and tell stories; in StoryMat [6], children move around a blanket while they make stories with tangible objects; and in StoryRoom [25] and POGO [9] children play with tangibles offering visual and sound effects that guide the storytelling activity. Collectively, this prior research suggests the promise of tangibles like CyberPLAYce as tools for children to creatively express themselves, to construct meaning, to learn new knowledge, and to communicate during storytelling activities. Novel for expanding tangibles into the dimension of space, our tangible learning tool, CyberPLAYce, aims to merge play and learning in the physical world while transitioning children from consumers of virtual and digital-centric technologies into technological innovators and cyber-playful storytellers.

III. DESIGN PROCESS

The CyberPLAYce prototype (Figure 1 & 3) is the result of several evaluative design iterations developed by our multidisciplinary, design-research team (two architects, an education specialist, a computer scientist, a robotics engineer, and six interaction designers). Our team initially explored the potential of linking tangibles, playful storytelling, and theories of knowledge construction with computational thinking for children. Subsequently, a common framework was developed for designing a tangible learning tool that would engage children in playful activity while enhancing their learning and storytelling experience. After pondering and debating the different aspects of the tool, including its physicality and its user experience, as well as considering digital media and learning theory, the participants formed sub-teams to develop early alternative prototypes, which converged during a follow-up design phase as prototype A-1 of CyberPLAYce (Figure 2: RIGHT). The first two prototypes (Figure 2 & 12) included magnetic, rectangular panels; nearly two-feet measured diagonally, that served as building blocks for constructing cyber-physical environments imagined by children.


Figure 3. CyberPLAYce (current prototype - B-1) Children engaged in our cyber-physical storytelling study

Our research team considered various means for building a large physical structure with CyberPLAYce panels. An early empirical study with children indicated that lighter panels with more robust joints (connections) were required to enhance the development of children's spatial computational-thinking skills. As a result, the third and current prototype of CyberPLAYce, Prototype B-1 (Figures 1, 3, 11, 14 & 15) was designed and fabricated following the feedback, observations, and usability studies of our studies with Prototype A-1 & A-2. This paper focuses on the design and evaluation of the current CyberPLAYce prototype (B-1) and it is the first to present results from our study with prototype B-1. CyberPLAYce prototype B-1 was built from lighter but still robust materials – insulation foam boards and corrugated plastic sheets – to make the panels as light as possible for children to make larger structures. To facilitate imaginative design activity and promote spatial computational-thinking, Prototype B-1 features triangular-shaped panels providing children the opportunity to build unlimited forms of their imagination. Additionally, a friction joint was designed and built for Prototype B-1 using Velcro to make temporary connections between the panels while improving the opportunity for children to construct larger structures in the space.

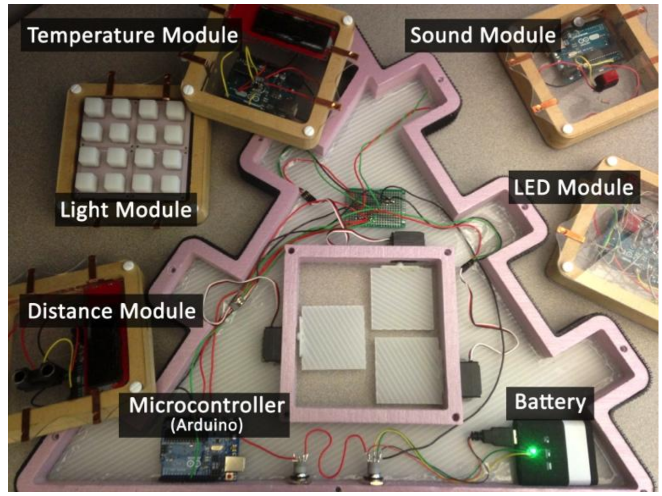


Figure 4. CyberPLAYce Components (Prototype B-1)

The CyberPLAYce construction kit is comprised by the open–source Arduino microcontroller and software platform [22] and five hand-sized, magnetic modules embedded with a variety of electronic components: a light module, a temperature module, a sound module, a distance module, and an LED module (see Figure 4). The modules are wirelessly connected so that young users receive instant feedback during plug-and-play activates. Through play with these components of CyberPLAYce, children become comfortable with the panels and modules. Additionally, young users are provided matching non-electronic *icon cards* (Figure 5, LEFT) allowing them to quickly compose pattern sequences to map ideas, stories and class content. The pack of icon cards include a sound card, a temperature card, a Wi-Fi card, a distance card, a screen card, and a push-button card. The icon cards, visualize different plug-and-play activities that can be done through the CyberPLAYce modules. Moreover, students are provided *action cards* (Figure 5, RIGHT) to spark their imagination with making connections between the icon cards and various activities featured on action cards. The action cards are changed for each scenario; however, the icon cards remain the same for all CyberPLAYce activities.

Figure 5. CyberPLAYce icon cards and action cards to spark students' imagination

The following scenario, developed by the education specialist leading the effort, envisions how CyberPLAYce operates in the classroom setting:

> *One day, in a classroom of 8 year olds, Mr. Smith asks the students to think of the routine tasks the students perform each morning at home. Then he tells his story of "Jane".... 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….

When children break down a story or problem (such as presented in Jane's story) into smaller, more manageable segments, they better understand, interpret and construct knowledge (i.e., they think computationally) [34]. In this way (Table 1), Jane's story is broken down, with each story segment defined by concepts and actions. CyberPLAYce's icon and action cards help children construct pattern sequences and map-out story ideas of their own. Etched into the electronic modules are the same images appearing on the icon cards, providing real-time feedback when children plug the modules into the panels and assemble the magnetic panels into spatial constructions. Children initially match the icon cards with the associating electronic modules, and then find the order of the story segments by putting the pieces together. The segments from the CyberPLAYce scenario are matched to various input-output activities (Table 1): a linkage of cards, modules and ideas that suggests how CyberPLAYce might provide children the means to think, understand, learn and share through a multi-media, tangible experience.

IV. Empirical Study

The empirical CyberPLAYce study posits two research questions:

(1) Can children comfortably use the technology during the storytelling or problem-solving activity?;

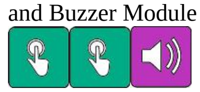
(2) How does CyberPLAYce support children's storytelling experience and enhance their spatial computational-thinking?.

To test the CyberPLAYce experience, an evaluation of the final prototype was conducted at Hunter Middle School (pseudonym) in S. Carolina, USA over three days. Each day, two pairs of children, ages 8-12, participated in a 2.5-hour evaluative session. Relative to the research questions posed, the sessions were designed to elicit data on the system's usability (Questions 1), and efficacy (Question 2). Overall, 12 children attend our cyber-physical storytelling study (N=12).

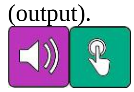
A. Research Activity

To gather data on whether children could comfortably use CyberPLAYce during interactive storytelling, children completed two main tasks, Tasks-1 and 2, for each session. In Task-1, children listened to a given story (Jane's story), and then were asked to retell the story through the icon and action cards. Children began by matching the story segments to the action cards, and followed by using the icon cards to identify different input-outputs that define each action. Subsequently, the participating children were asked to retell the story by plugging-in the associated CyberPLAYce modules into the panels according to the order of the icon cards that they had previously organized. In Task-2, the children were asked to choose at least six action cards out of the ten cards provided them, and then to match these action cards with the relevant icon cards. The action cards provided the children (Figure 6) pictured different yet familiar phenomena (e.g., a jungle, a GPS device, a car, a lion, and a thunderstorm). Subsequently, children handwrote on paper their own stories following from the prompts pictured on their selected action cards. Lastly, each group presented their composed story through paper and the CyberPLAYce components. A counterbalanced design was employed (i.e., in which one group told their story through the notes that they made on paper first and then they used CyberPLAYce to tell the story, while the other group completed the tasks vice versa) to minimize threats to validity by preventing any pre-knowledge attainment by the children.

1. The sun rises just before Jane's alarm goes off.
➔Peel off the cover of the light sensor (input) to activate Circle LED and Buzzer Module (output).

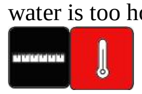


2. When Jane hears the sound of the alarm, she pushes a button to turn it off.
➔Push the button on the Buzzer Module (input) to turn it off (output).

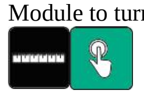


3. *Jane turns on her bedroom light and her room becomes yellow.*
➔Push a button on the 2x2 Button-Light Module (input) to turn on the yellow light (output).

4. Jane walks to the bathroom to take a shower, but first she tests the water to make sure it isn't too hot.
➔Display the distance on LCD Module (output) using the distance sensor. Use the Circle LED and X Module (outputs) to indicate if the water is too hot (input) using the Temperature Module.



5. After Jane showers, she runs back to her room to turn the light off.
➔Display the distance on LCD Module (output) using the distance sensor (input) when the child moves a hand away from the sensor; then the yellow light in a Button –Light Module on the adjoining panel turns on (output). Push the button on the 2x2 Button-Light Module to turn off the yellow light (output).



6. Jane sees a rainbow outside her window.
➔Push the button on the 4x4 Button-Light Module (input) to turn on the "rainbow" (output).

7. On the way out of her bedroom, Jane accidentally slams the door.
➔Activate the Flap Module (output) using the distance sensor (input).

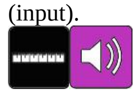


Table 1. The breakdown of Jane's story into segments, as a vehicle to thinking algorithmically and computationally

Figure 6. Sample of action cards given to children to create their own story for Task-2

Children completed Tasks-1 and 2 collaboratively while sharing ideas and communicating through the tangible tool.

During each session, the research team observed the storytelling activity, and made notes on how participants engaged with the cards and module and panel interfaces, and reacted to the tool overall. Immediately after the storytelling and story creation activities, the research team asked the children for feedback about their experience of telling stories through CyberPLAYce. The sessions were videotaped and the discourse transcribed.

At the conclusion of the sessions, each child completed a facilitated questionnaire (employing a Smileyometer as a 5-point Likert scale) that evaluated CyberPLAYce on measures of usability, aesthetic design and storytelling engagement. The results of the questionnaire (Table 2) indicate that most of the children enjoyed the process of story creation, discovery and storytelling, and found the CyberPLAYce suite fun and engaging. The participating children positively rated CyberPLAYce (with the overall average of 4.5 out of 5.0) on "storytelling motivation" which suggests that the children surveyed would use CyberPLAYce again to create and tell other stories, and CyberPLAYce may have helped them understand story concepts through a playful experience.

Our observation indicated that although three children seemed uncomfortable making stories at the beginning, all the twelve children engaged with the CyberPLAYce activities with pleasure. Meanwhile, two children reported that they thought it would be difficult to explain to a friend how CyberPLAYce works – something to consider.

To conclude, the observations and feedback received from the children and research indicated that:

1. Three children (out of 12) still found the plug-and-play activity frustrating when they were plugging electronic modules into the large panels. Friction must be reduced.
2. Two children had difficulty matching the icon cards to the associated modules; they suggested we color-code and name the cards and modules appropriately.
3. All the twelve children wanted more electronic modules, including ones with a sound recorder, a camera, and a large LCD screen to show pictures and hand drawings of visual representations of their stories.

Variable	Mean	Graph
How **attractive** …?	4.5	
How easy to **plug-n-play** modules …?	3.83	
How easy to **form space** …?	3.6	
How easy to **explain to friend** …?	2.5	
How **fun** …?	4.83	
How much learned **electronics** …?	4	
How much helped to **tell a given story** …?	3.5	
How much helped to **create your story** …?	4.5	
How much want to **tell stories** …?	4.83	
How much **icon cards** helped …?	3.5	
How much **modules** helped …?	3.5	

Table 2. Questionnaire results of the empirical study

B. *CyberPLAYce Supports Personal Expression and Spatial Computational-Thinking*

Our empirical study suggests that CyberPLAYce supports children in expressing themselves imaginatively through their interaction with peers and the various components of CyberPLAYce. Across the six groups of children, different imaginative interpretations of concepts were observed during the story-construction process. For instance, one group interpreted the sound card/module as: "*Sammy and Anna see a lion screaming in the jungle*."; while another group indicated that, "*Tommy and Jessica are speaking to each other*."; while the third group interpreted the sound card as "*Bob and Samantha are driving to South Africa*.". Quite often, children expressed themselves simply by laughter, elicited by unexpected events occurring to the characters of their story. The children frequently explained this laughter through expressive language such as: "*Something is making noise! Roar… It's a pink lion! Hahahah…*"

The empirical study allowed the research team to observe how CyberPLAYce might support children in thinking and expressing themselves computationally. We used CT practices (i.e., decomposition, pattern recognition, pattern abstraction, and algorithm design) as a starting point to identify more diverse competences within computational thinking. In our empirical CyberPLAYce study, the computational thinking practices were examined as below:

1. Decomposition: "*breaking down a problem or task into smaller and more manageable parts*" [3, 34]. In Jane's story the young participants engaged in breaking down the story into smaller story segments that may help them learn how to simplify complex problems by matching the icon and action cards.

Each student was provided a copy of Jane's story and a colored highlighter to identify story segments according to the icon cards. Subsequently, the students highlighted and numbered story segments in the order of the storyline (see Figure 7).

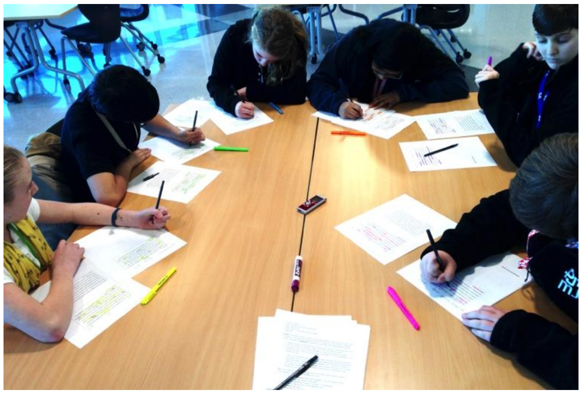


Figure 7. Children practicing in decomposition process of the computational thinking practices

2. Pattern Recognition: "*noticing similarities or common differences to assist in making predictions or shortcuts*" [3, 34]. In the empirical study, the children used pattern recognition to classify tasks while dealing with a big problem. Further, via recognition of the patterns featured on the cards, children may recognize opportunities to re-use visual patterns as they respond to different problems. The students' ability to recognize patterns was observed when they matched the story segments with the provided five icon cards including sound, temperature, light, push button and distance cards (Figure 8- LEFT).

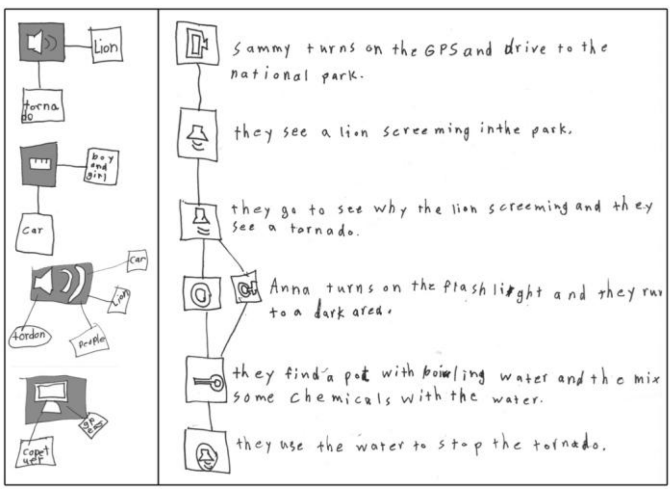


Figure 8. Story construction process employing computational thinking practices using CyberPLAYce

3. Pattern Abstraction: "*removing unnecessary information and representing an idea in general terms to solve similar problems or create a shortcut*" [3, 34]. In Jane's story, the children were given unnecessary cards to delete or ignore while seeking an apt solution to the problem. The children were also provided a situation in which multiple problems demanded the same response rather than a new response. For example, the light card and the associating module were used several times during various activities related to the study of light.

4. Algorithm Design: "*developing a set of step-by-step instructions and abstractions to solve a problem or complete a task*" [3, 34]. Many of the activities involved in decomposition, pattern recognition and pattern abstraction will require the child to create sequences of steps to solve a problem or complete a task. Algorithm Design helps young participants develop a step-by-step instruction method for creating a story that is suggestive of computational expression. Figure 8 shows one group's recording of the step-by-step process of story creation (Task-2), including the organization of the icon cards in the order of the storyline, the matching of icon cards with action cards (Figure 8, LEFT), and the development of the story segments in accordance with the created algorithm (Figure 8, RIGHT).

In a similar way, Figure 9 shows how a group of young participants matched the icon cards with Jane's decomposed story segments, and organized them in the order of the storyline. Through the created algorithm, children retold and recreated Jane's story with a combination of CyberPLAYce cards, modules and panels (Task-1). CyberPLAYce provided children a cyber-physical experience to learn computational thinking practices spatially while telling or making a story.

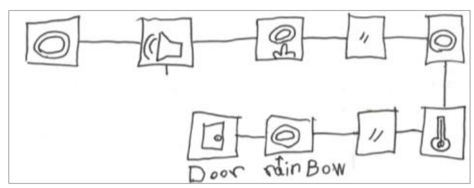


Figure 9. Children created an algorithm with organizing the icon cards in the order of the storyline

During Task-1, on each day, the first group of children collectively developed a linear story-algorithm (Figure 9) and the second group created a non-linear (tangible) story-algorithm with CyberPLAYce (Figure 10) in accordance with their findings following the CT practices. The first groups retold Jane's story through the linear algorithm (created on paper), and the second groups retold Jane's story through the non-linear algorithm which was constructed through the panels and modules of CyberPLAYce. Although the participants spent more time to construct the non-linear algorithms through the CyberPLAYce panels and modules, they found it unnecessary to check each piece of the algorithm with the original story to

Figure 10. CyberPLAYce study with Prototype B-1 at Hunter Middle School

remember the associating story segments during the storytelling activity. However, the second groups of children on each day were observed referring back to the original story to remember what the light icon refers to, and this was because the light icon was used five times in the process of the algorithm design. This indicates that the physical-spatial construction of the story algorithm in an abstract way helps children remember story segments better than telling a story from paper.

During the story-construction process (Task-2), when the children used CyberPLAYce, they were concerned with the physicality of the whole story along with considerations of directions, orientations, shapes and movements. On the other hand, the tangible algorithm created through the modules and panels of CyberPLAYce provided the 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 their story from the paper. In Task-2, children were observed to change their story several times while telling the story through the CyberPLAYce components to make their story more sophisticated and communicative in the spatial setting; however, we did not observe any changes while children were telling their stories from paper.

The conducted study provides a pathway to suggest how computational thinking practices can be taught and assessed inside and outside classroom settings.

V. DISCUSSION

In designing CyberPLAYce, we aimed to create a cyber-physical tool supporting new modes of thinking, exploring and interacting. CyberPLAYce is inspired by other learning tools, such as Lego Mindstorms [4], Cublets [32], Makey Makey [23], Circuit Stickers [17], and the iPad and its many learning applications. CyberPLAYce is however the outcome of our consideration of combinations of interaction modalities – physical, digital and spatial – in which we gauged how these different combinations enhance the personal, social, emotional and computational development of young children. In other words, CyberPLAYce provides children a tool that collectively offers different interaction types which distinguishes it from its precedents. In particular, CyberPLAYce represents a novel effort to expand cyber-learning to the dimension of space. We and the research peers cited in this paper concur that computational thinking combined with spatial thinking will prove key in helping to prepare today's students to meet the "workforce demands of the future, and to help solve some of the most pressing, intractable problems of our time" [7].

A. Letting Children Control the System

In the investigations reported here, we allowed children to employ different approaches to make their own story or, alternatively, to retell an existing story. Children browsed the cards, modules and panels of CyberPLAYce, and selected their own elements of communication. In the empirical study of Task-1, children 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. In this way, CyberPLAYce reflects Piaget's theory that "knowledge is not simply transmitted from teacher to student, but actively constructed by the mind of learner. Children don't get the ideas; they *make* the ideas" [19]. In CyberPLAYce, the construction of knowledge happens in the context of building meaningful artifacts [16]. After our empirical studies, it was telling that the participating children frequently asked for the opportunity to both make their own cards and alter the electronics of the CyberPLAYce modules (e.g. changing the sound, light-opacity, or flap movement pattern). These alterations are being considered to be incorporated into next CyberPLAYce prototypes. An important question for us and for the IDC community remains: *to what extent do we provide system customizability for children?*

B. Letting Children Control the Structure

One of our main intentions in designing CyberPLAYce was to provide children the opportunity to construct meaningful, spatial artifacts – an initial step towards STEM interests and careers. As a result, our team designed the early two prototypes (A-1 and A-2) including rectangular-shaped panels with neodymium magnets pasted on the edges of the panels (see Figure 11). This gave the children an opportunity to make connections between the panels in a limited ways. The design was not completely successful for the purpose of making large structures because of the weight and geometry of the panels.

Meanwhile, the children often had difficulty making connections between the panels.

Eventually, the final prototype was designed and built out of lightweight materials. Following the feedback received from the education specialists and the interaction design team, we decided to make triangular-shaped panels connected by friction joints (male-female connection) to establish temporary connections between the panels (see Figure 12). The triangular panels provided a better spatial geometry for children to make creative structures of their interest. Our current study in the classroom setting is mostly focusing on evaluating these spatial interactions afforded by CyberPLAYce.

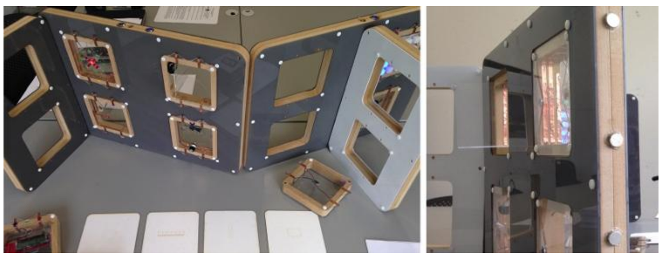


Figure 11. CyberPLAYce (Prototype A-2), neodymium magnets were used to make temporary connections between the rectangular panels

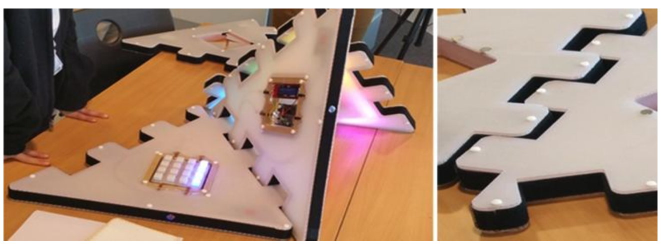


Figure12. CyberPLAYce (Prototype B-1), friction joint was designed to make temporary connections between the triangular panels

C. Assessing Computational Thinking

One challenge facing educators as well as researchers is the lack of widely accessible and validated approaches to assess computational thinking. Currently, assessment strategies tend to be specific to a computational thinking project, and do not benefit from innovative tools like ours. For example, Grover and Pea [15] point to a need for CT assessment strategies based on specific construct definitions incorporating relevant tasks and activities in physical and digital environments. We argue that the use of cyber-physical tools and environments for CT assessment may provide improved understanding of how learners apply computational thinking practices in more realistic situations than do a paper and pencil test.

The focus of our research was to build a cyber-physical-spatial learning tool that helps teach children how to think computationally, which involves decomposing a problem, recognizing and generalizing patterns, and developing a step-by-step instruction through a playful activity. This focus allowed for our investigation of the constructs of computational thinking, and helped us develop operational definitions (decomposition, pattern recognition, pattern abstraction and algorithm design) that facilitate monitoring of learning progress, and moreover evaluate the perception of CT by both teachers and students. For example, during our empirical study, we gave children printed handouts offering Jane's story. The children initially used colored highlighters to mark up different segments of the story (decomposition); they afterwards matched story segments to 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 guided our research team in its examination of children's computational thinking skills, focused particularly on how these young participants logically organize and analyze data while dealing with real-world problems.

Notably, CyberPLAYce is not designed only for a specific scenario: it can operate across different scenarios. For example, our current classroom study considers different activities and solutions to prevent or slow global warming – a large-scale and complex problem. The process includes various solutions and tasks that may positively impact the problem of global warming. In this current study, children are required to seek solutions, employing CyberPLAYce to communicate their ideas (see Figure 13). In the process of this study, our team might come to imagine still other modules and cards that support children in constructing stories in creative and expressive ways.

Figure 13. Children engaged in our global-warming scenario

VI. CONCLUSION

As with any study, there are limitations to our findings. While the children who participated in our study were diverse in ethnicity and in literacy attainment level, we were still limited in terms of time and funding to recruit more students to participate. Nevertheless, as our intention was to support an iterative design process and not conduct a comparative study, the participation of a children yielded invaluable input on what was better or worse about the different iterations of CyberPLAYce, and in many instances, why. Through these iterations and the feedback received from children and several education specialists, we confidently refined our prototype to arrive at Prototype B-1. During our studies, the children enjoyed the physical and spatial elements of CyberPLAYce while developing their own ways of expressing ideas and stories. As we witnessed, the children's engagement with CyberPLAYce was enhanced as we redesigned and refined the prototype. Supporting our observations are the questionnaire results indicating that children comfortably used our final prototype during storytelling and story-construction activities.

While we do not seek to over-generalize the study results, our evaluations of CyberPLAYce are promising in terms of strategies for the design and evaluation of novel tangible learning tools for children. Schools and learning methods are frequently bound by rules, and mostly limited to books and perhaps, most recently, to iPads. CyberPLAYce attempts to introduce a new genre of learning –at once cyber, physical and spatial – aiming to enhance children's computational and spatial thinking skills through play and exploration. An exemplar cyber-physical learning system, CyberPLAYce can provide students a tool to perform problem-solving, decision-making, and task-analysis through interacting with real-world problems in an abstract way. This abstractionism builds upon tangible computing (i.e., non-linear thinking capacities) which can be extended to diverse disciplines such as mathematics, biology, architecture, and chemistry. Tangible programming involves teaching fundamental concepts from Computer Science (e.g. computational thinking capacities) through visual and physical affordances of modern technologies. Cyber-physical-spatial affordances offer children an environment to think three dimensionally while telling stories and solving problems. These technologies can provide children the opportunity to decompose complex problems to smaller segments and come up with a variety of ideas while considering the relationships between the segments in a 3D context. CyberPLAYce supports tangible storytelling and story-creation processes by offering children a tool to think and create stories spatially rather than following a linear storyline on paper. This opportunity helps them think about various interactions between story segments which is not possible when using a pen and paper to create and tell stories.

This cyber-physical-spatial learning paradigm also provides a transdisciplinary approach to the learning and education system. For instance, CyberPLAYce's major contributions are towards Computer Science, Education, and Architecture. Recently, the Computer Science communities such as TEI (Tangible Embedded, and Embodied Interaction) and IDC (Interaction Design and Children) have focused on tangible programming and computational thinking capacities through cyber-physical systems. Our CyberPLAYce is an example of designing and iterating such tools to teach programming and scripting in a visual and tangible way. 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 spatial and digital affordances within CyberPLAYce provides educators a tool to teach preliminary concepts in architecture and computational design to young learners while preparing them for future demands of designing and living in cyber-physical environments.

The research team will continue developing CyberPLAYce across teacher curricula, employing playful design principles and using multimodal learning environments. Rather than traditional learning methods and digital-centric learning technologies, we argue that we should design tools that act as mediators for play while bridging the digital and physical worlds (Figure 14). We will continue to strive to design cyber-physical-spatial systems to think with, to learn with and to express with.

Figure 14. CyberPLAYce Prototype B-1: Children engaged with cyber-physical activities afforded by CyberPLAYce

SIGNIFICANCE FOR IDC RESEARCH

For the larger IDC community, CyberPLAYce is a design exemplar that may be characterized as a case of *research-through-design*, focused on a tangible, interactive learning tool that, in a novel way, extends cyber-learning to the dimension of space. As computing becomes evermore ubiquitous in our everyday lives, notably in education, it will inevitably occupy the physical spaces we live and learn in, and increasingly converge with it to construct a tangible-interactive learning environment – a next frontier for IDC researchers.

SELECTION AND PARTICIPATION OF CHILDREN

In the CyberPLAYce study 12 children aged 8-12, from a STEAM Middle School in South Carolina, USA were recruited. The children were randomly selected amongst thirty students. All the students were given Parental Permission Form, completed and signed by the children's parents. Prior to the study, children completed Child/Minor Agreement Forms to participate in the research study. The study was conducted at the school over three days. Each day, two pairs of children participated in a 2.5-hour evaluative session.

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