J-IAMSTEM
Journal of Innovation, Advancement, and Methodology in STEM Education
Vol. 1, No. 1, pp. 1 - 12, January – February 2024
https://so13.tci-thaijo.org/index.php/j_iamstem

How to Code a Sandcastle: Fostering Children's Computational Thinking through an Unplugged Coding Experience

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Received: 16 Nov 2023 Revised: 23 Feb 2024 Accepted: 28 Feb 2024

Abstract

Computational thinking is a fundamental capability that equips individuals with critical 21st century skills. It encompasses problem-solving, algorithmic reasoning, and a deep understanding of the logical and sequential processes involved in coding and problem solving generally. While often associated with digital technologies, young children can develop these skills through unplugged coding experiences that do not require screens or devices. This article presents the concept of computational thinking, the importance of introducing it to young children, and the ways in which an unplugged coding experience, "How to Code a Sandcastle", fostered its development amongst a group of 4- and 5-year-old children. In framing the research, we delve into the foundations of constructivism and socio-cultural theory and, existing research in this field. Themes emerging from analysis of the video data capturing the children's co-play, are presented as narrative style vignettes that highlight the potential of unplugged coding play to empower young children with computational thinking skills, setting the foundation for lifelong learning and problem-solving abilities.

Keywords: Coding, problem-solving, children

1. Introduction

Computational thinking, often regarded as a 21st century literacy, has become a crucial skill for success in today's digital world. It underpins the problem-solving abilities, logical reasoning, and creativity needed in various aspects of life, from STEM (Science, Technology, Engineering, and Mathematics) fields to everyday tasks (Murcia et al., 2022). However, the development of computational thinking skills need not be limited to the older age groups. Young children can be introduced to computational thinking through unplugged coding play experiences that do not require computers or digital devices. They involve using hands-on materials and kinaesthetic learning to teach the principles of coding, algorithms, and logical sequencing. This approach allows children to develop the foundational skills needed for later digital coding while enhancing problem-solving, critical thinking, and creativity. By nurturing computational thinking abilities in early childhood, we empower the next generation with the tools they need to thrive in an increasingly complex and technology-driven world. Unplugged coding, which focuses on teaching coding concepts without the use of computers or electronic devices, has gained attention as a developmentally appropriate approach for nurturing computational thinking skills in young children (Lombardi, 2022). It offers a hands-on, tangible way for children to engage in the foundational concepts of coding, such as sequencing, pattern recognition, and algorithmic thinking, without relying on screens.

This journal article explores the concept of computational thinking, the importance of introducing it to young children, and the ways in which unplugged coding activities can promote its development. We delve into the theoretical foundations, practical implications, and existing research. The comprehensive overview of the development of computational thinking skills in young children is then elaborated with an example of an unplugged coding play experience, provoked by reading the children's story "How to Code a Sandcastle" by John Funk. This unplugged coding experience was a part of a larger digital play program and research project, title 'Creative Cove' that was designed to identify pedagogical principles supporting children's creativity and computational thinking development within digital coding experiences. The study involved five young children, their parents, and two early years specialist educators and used an action research approach. Narrative style vignettes, reflecting the 'voice' of the children, are presented and used to illustrate key findings emerging from the thematic analysis of the video data capturing the children's unplugged coding experience. The article concludes by providing practical recommendations for parents and early childhood educators.

2. Literature review and theoretical framing

The framework for the study draws from the literature reviewed in the areas of computational thinking, cognitive development in early childhood and practical applications with unplugged coding.

2.1 Computational thinking and its importance in early childhood education

To begin, we recognise that computational thinking is now a significant component of school curricula (Angeli & Giannakos, 2020). However, there has been a relative lack of attention given to children aged 3 to 8 (Hu et al., 2023). In their systematic review, Su and Yang (2023) found only 26 research articles on CT involving young children between 2011 and 2022. Apart from the scarcity of research, they also observe a lack of systematic knowledge on how to integrate CT into early childhood settings. While there is consensus on what CT comprises, there is less clarity on how it applies in early years learning. Wang et al. (2020) note a limited range in early childhood CT research, which has primarily focused on standalone robotics and programming. This research often emphasizes physical outcomes over the dynamic learning process (Hu et al., 2023). Furthermore, research in robotics and programming tends to overlook interpersonal and intrapersonal attitudes and mindsets such as perseverance and persistence (Gomes et al., 2018), limiting the opportunities for children to practice and develop CT processing in diverse ways (Lavigne et al., 2020).

While there is no universally accepted definition of CT and its practical application, most studies reference Wing (2006) who defines CT as "involving solving problems, designing systems, and understanding human behaviour, by drawing on the concepts fundamental to computer science" (p. 33). It is a broad, interdisciplinary concept that encompasses problem-solving abilities, algorithmic reasoning, and logical thought processes. Computational thinking involves approaching problems systematically, breaking them down into smaller, manageable parts, and identifying patterns and connections (Lee et al., 2023). It includes 5 key components, (1) Decomposition: Breaking down complex problems into smaller, more manageable parts. (2) Pattern Recognition: Identifying similarities and recurring themes within a problem (3) Abstraction: Focusing on essential information while ignoring irrelevant details (4) Algorithmic Thinking: Developing step-by-step procedures for problem-solving. (5) Evaluation: Assessing the effectiveness of a solution and making improvements (Lee et al., 2023; Valenzuela, 2020).

Furthermore, there is a general consensus that CT requires a thinking-doing approach, not merely doing (Sung et al., 2017), and should be regarded as a fundamental competence for every child (Voogt et al., 2015; Wing, 2006). Introducing computational thinking at an early age can enhance children's abilities to think logically and critically (Bati, 2021). Computational thinking not only aids in understanding technology but also fosters essential problem-solving and critical thinking skills that can be applied in various academic and real-life situations (Wing, 2006). For example, the ability to break down complex problems into simpler, more manageable parts, enables children to tackle tasks more effectively, whether it's organizing their toys, solving puzzles, or understanding the structure of a story. Consequently, children who can identify similarities and differences, by recognising patterns, can apply this skill in learning mathematics, language, and science. Abstraction abilities are evident when children can focus on the essential parts of a problem while ignoring irrelevant details. We see this when children are identifying the main idea of a story or simplifying a complex game into its basic rules. Developing step-by-step procedures for solving problems is evidence of algorithmic thinking which children apply to everyday tasks, from getting dressed in the morning to completing a block construction when playing. The ability to evaluate the effectiveness of a solution and make improvements is also vital in computational thinking. Saxena et al. (2020) provided evidence that children aged 4 to 6 could demonstrate competencies such as decomposition, pattern identification, and abstraction. However, these skills need to be nurtured through the design of age-appropriate digital technologies and integrated learning experiences that accommodate different developmental competencies (Su & Yang, 2023; Bati, 2021).

2.2 Cognitive Development in Early Childhood

Early childhood, often defined as the period from birth to around age eight, is a crucial phase in cognitive development. During this time, children experience rapid cognitive growth, and their brains are highly receptive to new information and learning experiences. Key developmental milestones in early childhood include language acquisition, social interaction, and the ability to form abstract concepts. Cognitive development in early childhood is heavily influenced by various cognitive theories, including Vygotsky's Socio-Cultural Theory, Papert's Constructionism, Piaget's Constructivism, the Information Processing Theory, and Bruner's Theory of Scaffolding. These theories highlight the importance of social interactions, hands-on learning, and the role of educators in facilitating cognitive growth. They provide the theoretical underpinnings for the integration of computational thinking skills into early childhood education.

Cognitive development in early childhood is a dynamic and multifaceted process that lays the foundation for a child's lifelong learning journey. Theoretical frameworks play a crucial role in shaping our understanding of how children acquire knowledge, solve problems, and develop key cognitive skills during their formative years. This literature review delves into two prominent theories that underpin cognitive development in early childhood: Lev Vygotsky's Socio-Cultural Theory and Seymour Papert's Constructivism.

Furthermore, it explores how these theories are applied in the context of unplugged coding experiences, offering young children a unique opportunity to develop essential cognitive skills.

Socio-cultural theory informed by Vygotsky (1967) has had a profound impact on the field of developmental psychology, particularly in understanding how social interactions and cultural context shape cognitive development in children. Vygotsky's theory emphasizes the notion that cognitive development is fundamentally a socially mediated process, and the role of cultural tools in shaping children's cognitive abilities. Vygotsky (1978) introduced the concept of the Zone of Proximal Development (ZPD), which is the difference between what a child can do alone and what they can achieve with guidance from a more knowledgeable peer or adult. The ZPD highlights the importance of scaffolding, where a more competent individual provides support to help a child accomplish tasks just beyond their current capabilities. Unplugged coding activities can be seen as a fertile ground for the application of Vygotsky's theory, as they often involve collaboration and guidance from educators and peers. Moreover, Vygotsky's emphasis on cultural tools, such as language and symbolic systems, aligns with the idea that unplugged coding experiences introduce young children to a new symbolic language – the language of code. This experience not only extends their cultural toolset but also provides a platform for cognitive growth as they begin to understand and apply this new language in problem-solving and creative tasks.

Papert's Constructivism, takes a learner-centric approach that views learning as an active process where individuals construct knowledge by engaging in hands-on, meaningful experiences. He proposed that children learn best when they are actively creating or constructing their knowledge (Papert,1980). One of Papert's influential ideas is the concept of the "microworld," which refers to a simplified, digital environment where children can experiment, explore, and learn through active engagement. Unplugged coding experiences can be seen as a real-world manifestation of this concept, even though they do not involve digital devices. These experiences provide children with tangible manipulatives and activities that allow them to experiment with coding principles in a physical, hands-on way. This constructionist learning environment is where the children become "computational thinkers" as they engage in coding. By creating and debugging their codes and algorithms, children develop a deeper understanding of mathematical concepts, problem-solving strategies, and computational thinking skills (Papert 1980). Therefore the emphasis is on the child as an active participant, constructing their own knowledge and meaning through exploration and experimentation.

2.3 Unplugged Coding experiences in Early Childhood Education

Unplugged coding play experiences can offer a developmentally appropriate and engaging means of introducing computational thinking to young children (Del Olmo-Muñoz et.al, 2020). These experiences are teaching coding concepts and computational thinking without the use of electronic devices, such as computers, tablets, or smartphones (Lombardi, 2022). Instead, it relies on hands-on, physical activities, movements, and tangible manipulatives as explored by Saxena et.al. (2020), in their exploratory study for cultivating computational thinking. Unplugged coding activities aim to make abstract coding concepts tangible and accessible to young children, allowing them to learn through play. Using tangible manipulatives allow children to physically see and manipulate the elements of code, leading to a more concrete understanding of coding concepts. Children are encouraged to think logically, plan steps in advance, and understand the cause-and-effect relationships in coding and problem solving more generally.

3. Methods

The Creative Cove: Digital Stay and Play program was designed to explore and identify pedagogical principles that support children's creativity and development of computational thinking within digital coding experiences. The 10-week program began with the unplugged coding experience and then evolved to include collaborative play with a range of digital coding devices (various coding robots and iPads).

3.1 Research design

The research embedded into the Creative Cove program was grounded in the principles of action research, emphasizing a cyclical process of planning, acting, and reflecting. Action research was particularly well-suited for the exploration of pedagogical principles as it allowed for continuous assessment and refinement of the weekly teaching and learning strategies. Two early years specialist educators were positioned as practitioner-researchers. Their role involved planning and facilitating the weekly coding sessions and engaging in reflective discussions and video analysis as members of the research team. Their expertise in early childhood education ensured the sessions aligned with early years pedagogical principles.

3.2 Participants

A focus group of participants were invited to join the research project from the members of the Science Discovery Centre hosting the Creative Cove program. Parents and their children were provided with research ethics information letters and signed consent forms. There were five children, aged 4- and 5-years, participating. This mix included three boys and two girls. Each child participant was accompanied by a parent. The parents were actively involved in both the digital play experiences and the research project. Parents co-played with their children, participating in the coding experiences alongside their children. Their role was to guide their children during the sessions but not take over the children’s play and problem solving.

3.3 Data collection

A multifaceted approach was taken to data collection, ensuring rich understandings of the participants' experiences were captured. Firstly, the weekly digital play experiences were video recorded, using four cameras that captured different angles of the room. These video recordings allowed for the detailed examination of children's interactions, behaviours, and problem-solving strategies. To maintain the integrity and security of the collected data, consistent data management protocols were followed. Video data was removed from the cameras and uploaded to the university's online research storage, offering a high level of online security. In addition, each week children were encouraged to capture and represent their personal experiences through their annotated floor book drawings. Parents actively collaborated, writing the annotations, or transcribing the child’s conversation accompanying their floor book drawings. These drawings provide an additional perspective on children's experiences, as they illustrate their understanding and engagement with the coding challenges.

Each week, following the digital play experience, the research team met to debrief and share reflections on the activities, interactions, and the children's progress. The practitioner-researchers maintained detailed memos to document their reflections, thoughts, and insights. These memos served as valuable qualitative data and provided context for the video analysis.

3.4 Data Analysis

The first stage of data analysis involved the creation of time-stamped episodes or "snippets" from the video recordings. These episodes were extracted based on specific criteria, focusing on moments when children demonstrate computational thinking and coding capabilities. These selected segments formed the basis for further detailed analysis and the generation of detailed learning stories. The narrative-style learning stories were crafted for each weekly session, with a child and group focus, to capture critical learning episodes and interactions. These stories provided a structured framework for analysing the qualitative data, offering valuable insights into the development of computational thinking and creativity within the coding experiences.

4. Findings

Themes emerging from the analysis of the unplugged coding experience, “How to Build a Sandcastle” were captured and elaborated in the following narrative style vignettes.

4.1 Vignette 1: Computational creativity and problem solving.

In the imaginative unplugged coding session, Ethan showcased his computational thinking capabilities. As the session commenced, Ethan was instantly engaged with the educator’s reading of the story, “How to Code a Sandcastle.” The challenge for the play session was set by the educator, code your ‘robot’ (co-playing child) to build a sandcastle by stacking three cardboard boxes. Ethan, assuming the role of the coder, seized the opportunity to demonstrate his computational skills. With a stack of coding cards at his disposal, Ethan eagerly began designing the robot's pathway, offering sequenced instructions that included directional language. The coding grid on the floor became a canvas of his creativity, filled with green forward cards and a red right turn card, meticulously positioned to guide the robot, his peer Wendy. However, a coding problem emerged, stalling the robot's progress. Undeterred, Ethan recognized the issue and added a red right turn card at the start of the sequence, empowering Wendy to turn in the correct direction. The Practitioner-Researchers’ posing of open, what if and why questions, helped focus attention on directions and solutions. Wendy and Aaron were also watching their gestures and movements as it helped their thinking and visualising of the required orientation and direction. A missing green forward card was identified, and Ethan's resourcefulness and creativity shone through as he repurposed a white card, labelling it as ‘pretend green’, allowing Wendy to continue her coded journey. As Ethan diagnosed issues and made necessary adjustments, he was resilient, demonstrating a problem-solving attitude, by persisting and putting his ideas into action.

4.2 Vignette 2: Imaginative play and fostering collaboration.

While turn taking in another unplugged coding adventure, Aaron took centre stage as the initiator. He led the way, creating a new challenge by arranging the boxes from largest to smallest, providing a visual demonstration of his computational understanding. The children collaborated, taking roles within the team. Aaron watched intently as Ethan was using coding cards to represent the robot's path, showcasing an eagerness to translate computational thinking into tangible actions. As Wendy followed the coded instructions, Aaron and Ethan stood by, ready to debug any problems. Aaron, demonstrated

computational creativity as he identified a coding error and corrected it using a yellow card which, allowed Wendy to continue. He joyfully celebrated her success! Aaron's leadership emerged as he offered ideas to his peers, fostering teamwork and collaboration. Encouraged by Aaron, the children practiced clear and accurate communication, tried out ideas and learnt form errors. As Aaron's turn to be the robot approached, the play extended beyond the floor grid alone. The children engaged in creative storytelling, introducing a 'battery' concept to maintain the robot's energy, as Aaron acted-out 'running out of energy'. Lachlan eagerly observed as the robot followed the coded instructions, but his patience dwindled as he waited for his turn. His anticipation led to a revelation, the need to maintain the robot's 'battery'. He created a charging point using a drawn visual cue, ensuring the robot's energy levels remained intact.

Lachlan's innovation extended beyond the coding grid, demonstrating the connection between unplugged coding experiences and tangible solutions. His involvement contributed to and reflected the collaborative nature of the coding experience. The children's imaginative play transcended the coding grid, fuelling their drive for computational thinking and problem-solving.

4.3 Vignette 3: See what we did: Multimodal representation of the robot game.

When talking about what they had done in the play experience, the unplugged coding task was referred to as the 'robot game', reflecting the children's imaginative engagement with computational thinking. The children enthusiastically talked with their parents and creatively represented their experience in a personal floor book with the Practitioner-Researcher. The children's drawings in their floor books captured the essence of the robot game. The children's joint effort in debugging and problem-solving illuminated the benefits of teamwork and collaboration in computational thinking. This was captured differently by each child as they shared their actions and learnings with pictures, symbols, and words. Aaron drew numerals to represent the frequency of instructions, while Wendy's representation (Figure 1) and explanation of her drawing was about the sequence of 'steps' in the coding. As she was talking, if a move was repeated, she would trace back over the arrow, so frequency was captured by the boldness of the symbol. She also represented the whole sequence in a birds-eye view of the coding grid with dots showing the position. Both Aaron and Wendy captured the repeating nature of a code in a sequence. Lachlan was particularly excited and energetic with his drawing, capturing what he described as a "super code". He specifically drew and talked about icons which he said were the ‘fix button’ and ‘erase’. Sally’s drawing showed the ‘blocks’ or pathway taken by the robot. She laughingly talked about the “silly codes and robot that goes offline.” Ethan’s representation (Figure 2) elaborated his experience and was surrounded by rich conversations that showed his understanding of position and orientation. He talked about the position of the robot in relation to the floor grid and, intentionally used arrows, indicating the start point, direction, forward, back and turn. Originality was evident in all the children’s drawings and their representation was fit for the purpose of sharing their experience and learning. With agency, the children were demonstrating both creativity and computational thinking in their problem solving.

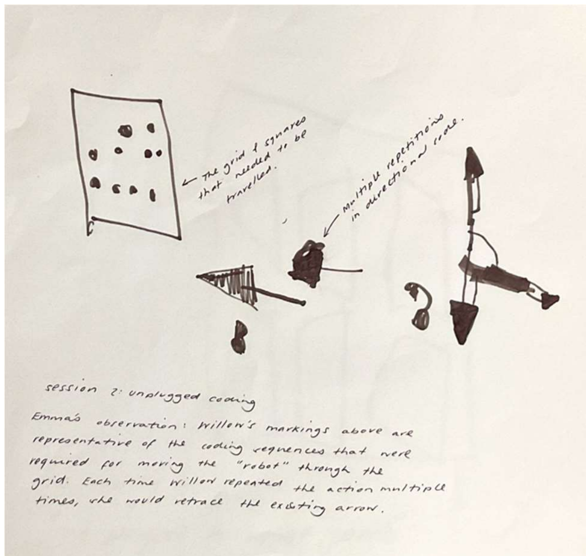

Figure 1: Wendy’s floor book recording

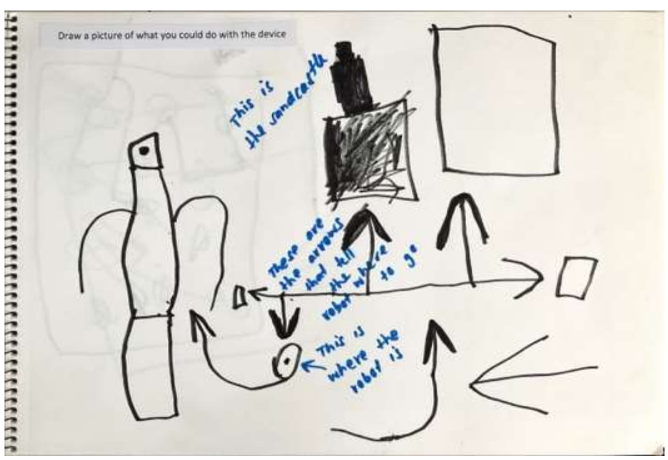

Figure 2: Ethan’s floor book recording

5. Discussion

The findings of the study reveal the effectiveness of the unplugged coding experience in promoting the children's computational thinking and creativity. Through the narrative-style vignettes, we highlight how the children actively engaged in creative problem-solving, collaboration, and imaginative play during the unplugged coding challenge. It was evident that the children were using algorithmic thinking and decomposition as they broke the complexity of the coding challenge into its parts. Like the study conducted by Lee et.al (2023), the children approached the task systematically, breaking the problem into its parts and connecting the symbolism of the coding cards with the robots' movements. The children's ability to represent their experiences through drawings and symbols in their floor books illustrated their ability to reflect, evaluate and determine what worked for them as they completed the challenge. In drawing, they practiced abstraction by focussing on only the essential parts of the learning environment and the actions that contributed to a successful outcome. Each of these described processes characterise the children's use of computational thinking during the experience. As a creative product, the children's coding sequences were original each time and fit to the purpose. They demonstrated computational thinking and creativity by identifying pathways, sequences and resolving coding errors. They were resilient as they tried ideas, identified errors and, then put their learning into action as they tried again.

Socio-cultural and constructivist theories emphasize the importance of social interactions, hands-on learning, and the guidance of educators in facilitating cognitive growth. The importance of the Practitioner-Researchers' pedagogy was highlighted through the video analysis and the influence it had the children's development and demonstration of computational thinking. While guiding the experience the Practitioner-Researchers were observed scaffolding learning by using open questions, listening to children's ideas and providing time for them to explore, try out ideas and learn from errors. They also scaffolded children's understanding of more abstract concepts by demonstrating and physically modelling these ideas. In this way, children were engaged by a more knowledgeable other, in their zone of proximal development (Vygotsky, 1978), that being the Practitioner-Researchers but also at times their peers. The pedagogical principles related to the use of hands-on, physical activities and movements for supporting children's computational thinking were also evident in the exploratory study conducted by Saxena et.al. (2020). This provides converging evidence supporting the generalisability of these principles for fostering children's computational thinking. Generalisable elements were evident in both the design of the learning experience and the pedagogical practices of the Practitioner-Researchers during the children's unplugged coding play.

The inclusion of the tangible coding cards in the learning environment, supported the children in using symbolic representation of direction, encouraged active engagement, collaborative teamwork and the use of trial and error in creatively resolving problems. The coding challenge, to build a sandcastle, was a kinaesthetic learning experience where children used whole body actions and hands-on manipulation of the cardboard boxes to support their computational thinking and solution to the challenge. Based on a solid theoretical foundation (Papert,1980; Vygotsky 1967), the Practitioner-Researchers engaged the children through guided play and focussed their attention on the concrete elements in the environment that could assist their computational thinking. Similar use of physical objects such as cards, puzzle pieces, or even everyday items like building blocks has been reported to foster children's computational thinking (Lombardi, 2022; Saxena et.al., 2020). Including physical manipulation of objects and materials into the unplugged coding challenge created connects to various learning styles, including kinaesthetic learning which, provided multimodal opportunities for children to construct understanding. The tangible cards or manipulatives serve as a visual representation of the code, allowing children to experiment with sequencing and logic. Embedding the cards into the activity allowed the children to see, touch, and manipulate coding concepts, making them more tangible and concrete. They encourage children to think logically, plan steps in advance, and understand cause-and-effect relationships, promoting a deeper understanding of coding and problem-solving.

Children's imaginative play and teamwork was fostered by the design of the experience and resourcing of the learning environment. Inclusivity was evident in the open nature of the challenge as the children could bring their unique abilities to the collaborative unplugged coding play. The research also showcased the importance of social interaction and collaboration in children's learning, as children took turns in coding, sharing ideas, scaffolding others learning and resolving challenges and mistakes together. The design of the experience and the guiding from the Practitioner-Researchers promoted social skills, teamwork, and cooperative communication. The playful challenge, surrounded by the rich and appropriate resourced environment reflected what Papert (1980) referred to as a 'microworld'. The children were exploring and learning coding capabilities that underpin computer science in a simplified non-digital microworld, where they were using their imagination, being creative and learning through collaborative active engagement.

6. Recommendations

The integration of unplugged coding into early childhood education requires careful planning and consideration. Play-based learning approaches can be effectively used to embrace unplugged coding experiences. The benefit is that play is a natural way for young children to learn and explore, and hence develop computational thinking capabilities. Early childhood educators and parents can incorporate unplugged coding experiences into young children's play and learning, through storytelling, presenting provocations and setting intentional challenges. These activities can be integrated into classroom lessons, children's creative playtime, or even as family activities at home.

When designing and planning unplugged coding, it is important to consider children's developmental stages, and strategies for actively engaging with children while guiding play and enabling their agency. The use of intentional dialogic learning conversations with children, based on open questions and actively listening to and valuing all children's ideas can encourage co-play and teamwork. Challenges can be designed that require collaboration for a shared outcome and success. Activities that are designed for group play, will promote collaboration and teamwork amongst children. Importantly, children working together to solve coding challenges, fosters social interaction and communication skills.

In the sandcastle building challenge, the children actively engaged with the materials, hands on learning, moving, arranging, and manipulating objects to create code sequences. This hands-on approach is recommended for enhancing children's understanding of more abstract coding concepts. Allowing children to learn coding principles without the use of digital devices, in these tangible and active ways, offers a bridge between concrete, real-world experiences and abstract computational concepts, making them more accessible and engaging for young children.

7. Conclusion

Children are growing up surrounded by technology, and it is becoming increasingly important to introduce them to the fundamental concepts of computational thinking and coding from an early age. Hence, the significance of this study lies in its potential to inform educational practices and curriculum development. By examining the theoretical underpinnings of computational thinking and its intersection with early childhood education, we offer practical insights for educators, parents, and policymakers. This study explored the importance of introducing computational thinking early in education and provides a strong theoretical framework for doing so. In the unplugged coding session, the children's creativity, agency, and computational thinking were on full display, transforming their play into a vibrant and imaginative learning experience. The narrative vignettes illustrated the rich and diverse experience of each child, highlighting collaborative efforts, creative problem-solving, and imaginative play. The empirical evidence supports the efficacy of unplugged coding play experiences and provides a basis for pedagogical decisions that can positively impact children's development. By incorporating principles of socio-cultural theory and constructivism into the unplugged experience design and guiding of children's learning, we aim to empower children to become creative thinkers, problem solvers, and active learners ready to embrace the challenges of the 21st century.

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