Learning computational thinking through embodied experience: a proposal of a framework

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Abstract: This study is implemented with a focus of discovering how students use the practice of embodied learning to gain knowledge of computational thinking (CT). An intervention was executed at an elementary school in a midwestern state, where students used a marker free virtual reality system to engage in a task that requires them to use the CT concepts and skills. Students participated in the path finding activity within the AR system, and demonstrated accounts of how they use their body to express their understanding of abstract CT concepts. Moreover, the affordances of the AR system were integrated to the student's learning experience, furthering the discussion of how student's embodied movement within the virtual world influences their learning outcomes of CT concepts. As an attempt to analyze the embodied learning experience of abstract notions, the researchers developed a coding framework that introduces the mapping of abstract CT concepts and the tangible embodied action that reflects each concept. This short paper thus presents the framework for embodied computational thinking skills, and further elaborates on the future implications of the on-going work.

Introduction

Computational thinking is proposed as being a universal skillset for everybody, including children. This initial vision of computational thinking is being relaunched over the past years. While the content of early childhood education has been focusing predominantly on primary literacy and numeracy, schools are increasingly understanding the importance of teaching basic computational thinking skills across all K-12 levels (Chalmers, 2018; Kafai & Burke, 2014). Now, many researchers are turning their focus towards effective STEM education in early childhood (Chalmers, 2018) and effective ways of teaching computational thinking to young children (Wing, 2006). However, computational thinking education holds the complexity of having to facilitate students' conceptualization and understanding of abstract concepts. This speaks to the gap in research, which is the lack of studies that discover effective strategies on teaching and assessing computational thinking to young children. Drawing on such chasm, this study conducted an intervention that proposes innovative teaching methods using principles of embodied learning. Students who participated in this study engaged in a path finding task within the AR system and used their movements and gestures to make sense of the abstract symbols, which forms the very foundation of computational thinking skills. Student's embodied learning experience was video, and audio recorded and was utilized to develop a framework for embodied computational thinking skills. The purpose of the study is to examine the influence of embodied experience in the conceptualization of children's computational thinking skills. The study goes further to uncover how, and the extent to which the bodily movements positively influence children's meaning making of abstract concepts.

Computational Thinking

The term computational thinking was introduced in the 1980s by Seymore Papert in the MIT Artificial Intelligence Lab. In that work, children played with text-based programming language to control a floor turtle robot. The term itself emerged from the designed based constructionist programming environment. Initially closely linked to the field of computer science and engineering, computational thinking is now recognized to share several similar characteristics with mathematical thinking and scientific thinking (Bers., 2010). At its core, computational thinking involves abstracting concepts from cases and selecting the right abstraction (Bres., 2010). Papert (1980) provided an initial definition characterizing it as "ways of algorithmically solving problems and the acquisition of technological fluency". Subsequently, Wing (2006) framed computational thinking as "a process that involves solving problems, designing systems, and understanding human behavior by utilizing the basic concepts of computer science", and expanded the conceptual framework of the term. Building on these foundations, Ching et al. (2018) similarly defined computational thinking as "a set of thinking skills, processes, and approaches to solve complex problems".

However, due to the origin of the concept stemming from computer science and researchers' diverse interpretation of the term, various perspective exists regarding computational thinking practices. A prevalent viewpoint posits that computational thinking should be promoted by programming language courses and practices. Grover and Pea (2013) advocates for this perspective, identifying abstraction and pattern generalization, systematic processing of information, symbol systems and representations, algorithmic notion, structured problem decomposition, iterative, recursive, and parallel thinking, conditional logic, debugging and systematic error detection as the nine essential components of computational thinking. On an opposing stance, an alternative perspective advocates for the employing computational thinking across various subjects and disciplines. This viewpoint emphasizes the problem-solving attributes of computational thinking with a special focus on data collection and automatic solutions (Kong, 2019). The international Society for Technology in Education (2011) similarly articulates the core elements of computational thinking as defining problems, collecting data, representing data, identifying, and evaluating possible solutions, and generalizing problem solving processes. In a parallel, Borrega et al. (2022) proposed the basic components of computational thinking as the creation of logical artifacts, abstraction, and their computational representation. Concurrently, Lin et al. (2021) also presented algorithmic thinking, creativity, logical thinking, and problem-solving skills to be the core element of computational thinking. Gadanidis (2017), who examined the intersection between artificial intelligence, computational thinking, and mathematics education, suggested the key elements of computational thinking to be agency, modeling, and abstracting concepts beyond specific instances. The diverse array of perspective underscores the multi-faceted nature of computational thinking, offering insights into its applicability beyond the barriers of computer science.

Wing (2006) extends the application of computational thinking skills, by suggesting that "To reading, writing, and arithmetic, we should add computational thinking to every child's analytical ability". This definition proposed a contribution of the field of computer science to a broader spectrum of humanistic studies, emphasizing its universally applicable nature beyond the realm of computer science. Building on this potential, extensive research over the last couple of decades unveiled findings about computational thinking teaching and learning. And this followed different approaches in defining computational thinking, and the presentation of useful structures or frameworks. For example, Brennan and Resnick (2012) developed a computational thinking framework comprised of three dimensions: computational concepts, computational practices, and computational perspectives. The seven computational concepts suggested in this study-sequences, loops, parallelism, events, conditionals, operators, and data- have resonated across a wide range of future research. Similarly, Weintrop et al. (2016) proposed a taxonomy of computational thinking specifically applicable to mathematics and scientific practices, which includes data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices. This framework collectively contributes to the comprehensive understanding of the conceptual domain, varied dimensions, and applications in diverse educational settings.

Augmented Reality System

Contemporary educational discourse has increasingly focused on the potential impact of student's physical movement and gesture in their learning processes. Moving beyond the era where educational technology predominantly lied in the conventional use of input devices such as mouse and keyboards, emerging technology that provides immersive interface tools is enabling a highly embodied learning experience. Augmented reality (AR) technology stands as a prominent example among the immersive technologies that fosters dynamic and engaging learning environments, enabling learners to map their movement in real life to the content to be learned.

The pivotal inquiry in the use of AR pertains to how does this technology facilitates the alignment between the learning content and the physical movement. According to Johnson-Glenberg (2019), the feeling of presence and a sense of agency, the two core attributes of AR underpin its significant contribution to learning. A feeling of presence, which is an idea of one's body being positioned in a physical space, has already been connected to meaningful learning gains by a substantial body of literature. This recognition of presence will be enhanced through students interacting with the environment and artifacts in the augmented reality setting. Immersive technology also benefits learners by giving them a sense of agency, which is a belief that one has personal control over the environment by manipulating the environment and artifacts (Johnson-Glenberg, 2019). Johnson-Glenberg further posits that this sense of control and empowerment over one's environment differentiates AR from other screen-based educational technology that is simply gazed-based. Experiencing agency over multiple parameters in one's learning scenario promotes stronger self-direction, and responsibility for learning, leading to building better knowledge structures.

Learning gains from engaging with AR technologies has been discovered in various research. For example, Jang et al. (2016) demonstrated that medical students who directly manipulated a virtual anatomical structure using their hand movements and haptic gestures were more likely to recall the observed structures in the post-test compared to viewing groups. Similarly, Kontra et al. (2015) discovered that students who physically held the bicycle wheels and tilted the axle showed higher learning gains in the understanding of angular momentum compared to the controlled group. Building on the literature, this study plans to further investigate the potential effects of AR technologies in learning computational thinking skills, with a specific focus on the principle of embodied cognition.

Embodied Cognition

Embodied cognition is grounded on the theory that the mind and body is inextricably linked together. Proponents of embodiment believe that cognition is not a process exclusive to human mind but is an interconnected system of multiple levels of sensory function, motor functions, cognition (Wilson, 2002). Because human cognition is deeply rooted in both our mind, body's interaction with the world, and our perception of our body, learning and understanding of abstract concepts are heavily influenced by the physical movement taken by our bodies. One of the cornerstones in understanding the embodied cognition literature is the claim that cognition is situated (Wilson, 2002). According to the situated cognition theory, cognitive processes are carried out within text relevant contexts, during which process perceptual information continues to impact information processing, and motor activity is subsequently executed in a way that influences the context in task-relevant ways. Moving around the room to imagine how to place furniture is presented as an example how cognition works in specific contexts in par with motor activities. Another mechanism of understanding how cognition is body based is the idea of off-loading, that is cognition is distributed to different parts of our body. Analogous to the use of fingers for numerical counting, he application of this principle to computational thinking and symbol comprehension allows students to strategically manipulate their body axis and orientation whilst engaging in developing the mental structure of abstract concepts. This movement of the body serves a role of reducing load on mental resources by distributing information to be processed to the works of a body. This proposition is underpinned by the overarching notion of 'epistemic action', which is defined by an array of physical actions that make mental computation more reliable, easier, and faster. Epistemic actions are external actions mapped congruently with epistemic goals that reduces load in mental computation and is particularly salient in tasks involving the manipulation of external symbols, as observed in disciplines like algebra, arithmetic, and geometry (Krish & Maglio, 1994).

A substantial body of research suggests that gestures and the physical movement of one's body promotes the understanding of scientific concepts. Scherr (2008) postulates that the sensory-motor information promoted by gestures plays a pivotal role in idea construction in learning classical mechanics. In a similar manner, Bruun and Christiansen (2016) developed classroom activities using the image schema that captures the kinesthetic experience of our body in learning core concepts in basic physics, such as liner motion. It is discovered in such research that the use of embodiment in the meaning making process of abstract notion in scientific fields bridge the phenomenological gap between decontextualized abstractions and authentic experiences. Nikolopoulos and Pardalki (2020) incorporates the element of embodiment by utilizing it as a form of dance workshops where students identified with movement of particles by performing a choreography depicting how particles interact with one another. This activity sheds light on the phenomenological sense of embodiment where the subjective involvement in a first-person point of view highlights the centrality in student's expression of scientific concepts. Concurrently, Danish et al. (2020) devised a collaborative embodied activity where a group of students collectively embodied their conception of how particles behave as additional energy is given or taken away from the particles. This study analyzed how cognition and learning exists at an intersection of the individual and the community who are pursuing the same movement.

As advances in technology enables the integration of sophisticated educational tools into the embodied learning experience, researchers discovered how technology and the physical movement of the body could jointly facilitate cognitive processes. Shvarts and Gitte van Helden (2021) conducted a notable study where students learned trigonometry and developed an understanding of the graphical representation of the sine graphs. This comprehension was facilitated through the interactive experience with tablet-based technologies designed to foster sensory-motor coordination, thereby enhancing the conceptualization of intricate mathematical concepts. Danish et al. (2022) developed a mixed reality platform called GEM-STEP (Generalized Embodied Modeling-Science through Technology Enhanced Play project) where learners engage with a mixed reality environment by controlling parts of the artifact and acting out how they move. Students conceptualized the flow of energy through the ecosystem by exploring the mixed reality model by taking on a role of worms, rabbits, and a sun. In another GEM-STEP activity, students embodied movements of fish and algae, brining energy from the right source to keep the ecosystem alive. Students wearing tracking tags enabled the video and screen recordings, which were used for conducting a movement analysis. In parallel, a lesson in biology incorporated

GEM-STEP technology to help students understand the how bees communicate through dance and its connection to the pollination process. Students assigned to the embodied group role-played as bees and interacted with the simulated reality that represents a garden (Anton et al., 2023).

While heightened attention is being directed towards integrating advanced technology in designing and facilitating student's embodied experience, still the attempt to use AR (augmented reality) remains confined to the implementation of GEM-STEP activities. Also, these activities are predominantly concentrated in subject domains such as physics, biology, engineering, and mathematics. While the phenomenological and ecological use of students' body is discovered to significantly promote the meaning making process of complex and abstract notions in STEM, embodied cognition in the realm of computational thinking skills is yet to be discovered. Thus, this study seeks to fills this gap by to enhance elementary students' conceptual understanding of computational thinking skills through the embodied experience of interacting with the marker-less AR system. The learning activity is meticulously designed based on the foundational tenets of embodied cognition, positing that physical movement and gestures aid in comprehending computational thinking concepts, particularly symbols and sequencing. This process is believed to activate a more extensive portion of students' sensory systems and motor pathways, consequently forming stronger memory traces (Goldin-Meadow, 2011).

Method

Ten first graders and second graders in a small elementary school located in the Midwest participated in this activity in the spring semester of 2023. Students used an individual device to log into an augmented reality learning environment. In the AR system, students were able to see a chessboard like grid and asked to complete a path finding task in the grid. The task started out as scenario on a 2X2 grid but added complexity as students advanced to the next stage, the final task ending with a 5X5 grid (see Figure 1). On the grid, obstacles, keys, and the final goal were presented as virtual objects. Students had to navigate themselves on the grid to go to the final goal, without bumping into obstacles but at the same time collecting the keys.

Figure 1. Students navigating themselves to the end goal of the pathfinding task on the grid

The embodied practice of four directional symbols (move forward, move backward, turn right, turn left) was used for this path finding activity. Students were supposed to execute movements that represent each symbol by taking a step forward, taking a step backward, turning the body right, and turning the body left. The AR device could detect the movement of the user, providing immediate interactive feedback to the student whenever they take any step or directional change (see Figure 2). For example, when a student took one step forward, the AR produced a verbal cue "You just moved forward". This specific activity was designed with a goal to enhance students' understanding of computational thinking concepts, more specifically the idea of symbol and sequences. Thus, before engaging with the actual tasks, students went through a practice stage where they followed the instruction of the AR device by demonstrating the exact movement that represents the semantics of a directional symbol. For example, when there was a verbal cue from the device saying, 'please turn right', students were expected to do the exact movement, which was an indication of how the student's conceptualization of 'symbol' was expressed through one's bodily movements. Hence, the tasks provided learning experience of connecting the semantics of the directional symbol to their lived experience by engaging in an embodied activity.

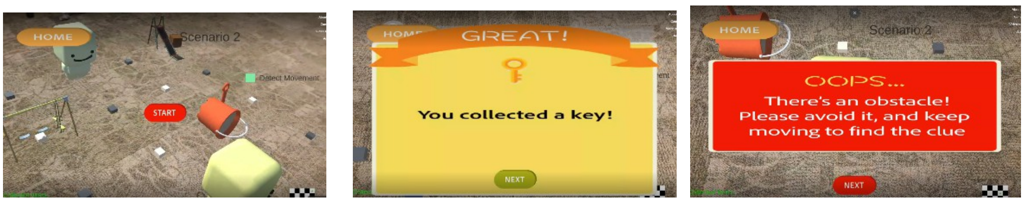

Figure 2. Interface of the path finding task in the AR system and its immediate feedback feature

The 10 students were able to successfully finish all the four stages of the task(see Figure 2). After the AR activity, students moved to another room to engage in a paper and pen-based performance test. The performance test asked a total of 8 questions that similarly required students to solve a path finding problem on a paper. Every session was video, and audio recorded, and analyzed to unveil how the embodied experience influenced the conceptualization of symbols.

Result

The goal of the study being discovering the embodied experience in learning computational thinking concepts, two researchers analyzed the video that captured student's movement of engaging in the 4 tasks. As a result of the analysis the researchers were able to develop a framework that maps the core elements of computational thinking into the embodied movement demonstrated by students (see Table 1). The analysis identifies three core elements of computation thinking that students learned by engaging in the activity: the recognition of symbol, the understanding of sequence, and debugging ability. The proposed framework presents how the students' movement demonstrates either a correct conceptualization of a core element (+) and an incorrect understanding of a core element (-). The demonstration in the video draws on the definition of the elements and elaborates how students' embodied action indicates they succeeded or failed to understand the computational thinking concepts.

The understanding of the first computational thinking concept, symbol, was expressed through the students' movement of correctly following the instructional cue from the AR device by demonstrating the exact movement of moving forward, backward, turning left and right. On the other hand, students who had difficulty understanding this concept demonstrated actions such as the inability to move accordingly to the verbal cues, walking sideways and walking diagonally. The most salient movement that represents this aspect of their experience is students embodying two symbols in one movement, for example, diverting the direction of the body simultaneously as one takes a step forward. This points to the understanding that the student could not grasp the idea that one respective step represents one symbol.

The conceptualization of algorithmic thinking, which is the understanding of sequence, is embodied in the movement of taking one step at a time by having short pauses in between steps and directional changes. On the other hand, lack of understanding in this element is demonstrated by embodied action of natural walking with disregard of the grid and the symbols. This element was frequently observed in students walking around the grid without giving any pauses in between. The conceptualization of debugging was embodied through the act of actively and deliberately maneuvering the tablet to navigate a new path, changing direction of one's body on the same spot when one meets an obstacle, and taking a step back when one bumps into an obstacle.

Table 1
Framework for embodied computational thinking

Element	Definition	Demonstration in Video
Symbol (+)	Student is able to express one's conceptualization of the symbol through embodied action	Student correctly follows the instruction of the AR device by demonstrating exact movement of moving forward, backward, turning left, turning right
Symbol (-)	Student is unable to express one's conceptualization of the symbol through embodied action	Student walks sideways
		Student walks diagonally
		Student moves one's body in a different direction than what one is instructed to
		Student diverting the direction of one's body simultaneously as one takes a step forward or backward
Algorithm (Sequence) (+)	Student is able to develop a step-by-step sequence to solve a given problem, and express it through embodied action	Student takes one step at a time by having short pauses in between steps or direction changes
		Student intentionally adjusts the direction of one's body, so the student's feet is positioned to a straight, not diagonal direction
Algorithm (Sequence) (-)	Student is unable to develop a step-by-step sequence to solve a given problem, and express it through embodied action	Student naturally walks without making separation (giving pauses) between each step
		Student takes multiple steps in a diagonal

		direction
Debugging (+)	Student is able to solve a problem by altering the codes and express them through embodied action	Student maneuvers the tablet to navigate another pathway
		Student stands still on the same spot to plan one's next steps
		Student does a right, left, backward turn on the spot to navigate another pathway
		Student takes step backward when meeting an obstacle
Debugging (-)	Student is unable to alter codes and express them through embodied action to solve a problem	Student looks for help from the researcher when meeting an obstacle

Alongside with the embodied framework that reflects the understanding of each computational thinking element, analysis revealed how student's cognitive processing of trying to make sense of the computational thinking concepts are demonstrated in their movements (see Table 2). This captured the moment of students going through a mental process of matching the verbal representation of a symbol (forward, backward, right, left) to one's embodied version the symbol. The incidents that demonstrate such learning moments are instantiated by students having a time lag between hearing the instructional verbal cue and actually conducting that movement, also students mistakenly tilt the direction of one's torso but ultimately regulating one's movement to follow the verbal cue instruction.

Table 2
Demonstration of cognitive processing and hesitance in learning computational thinking through embodied experience

Element	Definition	Demonstration in Video
Cognitive processing	Student goes through a process of matching the verbal representation of a symbol with one's embodied version of the symbol	Student demonstrates a time lag between lifting one's leg and taking a step
		Student demonstrates a time lag between hearing the instruction from the AR device and actually moving one's body to follow the instruction
		Student regulates one's incorrect movement and navigates oneself to a correct path (ex. tilting one's torso to the left before correcting one's step to the right)
Hesitance	Student shows reluctance to make any type of movement	Student very hesitantly turns right, left, or takes a step forward
		Student starts making smaller strides

Implications

The framework functions as a roadmap that provides guidelines for capturing and analyzing students' behavior indicative of the understanding of computational thinking skills. It also presents descriptive accounts of how students use their body to demonstrate or facilitate their conceptual understanding of core computational thinking elements.

Following up on this analysis, the researchers plan to analyze the video recordings using the framework as a coding scheme with an aim to uncover how using the body has an effect on learning gains in computational thinking. By conducting a video analysis, further research plans to unveil how the principles of embodied learning applies to the domain of computational thinking, adding to the scholarship of investigating effective learning strategies of abstract notions in younger children.

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