From Embodied *Doing* to Computational *Thinking* in Kindergarten

A Punctuated Motor Control Model

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ABSTRACT

We propose a motor control-based characterization of how computational thinking (CT) can emerge from embodied performance. The account is based on children's activity during a tangible coding task, and a mechanism proposed by cognitive and motor neuroscience studies. For the task, the child used navigational symbols (forward, backward, rotate right, rotate left) to program the movements of a tangible robot on a 2-D grid. We propose that the development of CT through this task can be understood in terms of "tool incorporation into the body schema." To illustrate the proposed mechanism, we use video data from one of three teaching sessions, where a group of four kindergartners learned to code using Cubetto (a tactile screen-free grid-based robotic toy). We argue that learning the task (i.e. being able to control Cubetto to perform goal-oriented movements) is challenging because the CT task requires learners to bridge three distinct discontinuities (spatial, temporal, and representational), to achieve control over the robot. We hypothesize that learners and facilitators are likely to engage in moves (both epistemic and pedagogical) that help bridge these gaps, and thus support the incorporation of the robot and its controller into the body schema. We characterize two such moves and explicate how they might support the incorporation process. The study is part of a larger program of design-based research aimed at helping young children develop CT.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI theory, concepts and models; Human computer interaction (HCI); Empirical studies in HCI; Collaborative and social computing.

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KEYWORDS

Tool incorporation, Embodied learning, Computational thinking, Early childhood education

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1 INTRODUCTION

There is a growing interest in introducing coding to young children through the use of screen-free robot coding toys [14, 17, 28, 29]. This is partly because of the popularity of coding as a 21st-century skill, advancement in the area of low-cost physical computing technologies, and the demand for "unplugged" or screen-free tangibles to learn programming. Together, these have created a conducive ecosystem for commercial ventures to manufacture off-the-shelf robotics coding toys at scale. These commercial coding toys allow early childhood educators with minimum or no prior background in computer science to introduce coding to young children [29].

Reimagining computing to make it accessible to young children has its historical roots in the 1960s when Wally Feurzeig, Seymour Papert, and Cynthia Solomon designed the Logo programming language. Logo allowed elementary school children to interact with a virtual agent – a turtle – by writing simple instructions to make it draw graphics on the screen. From the text-based interface of Logo, there has been a shift toward visual programming languages. Scratch is among the most widely used block-based visual programming languages and has millions of users worldwide. It has another variant, ScratchJr that is especially designed for ages 5-7 years which allows the creation of interactive stories and games via block-based (graphical) coding. However, many early childhood education classrooms have a "no screen-time" policy, which makes some of these developmentally appropriate digital applications ineligible for classroom use [9]. Hence, practitioners have leaned toward screen-free tactile interfaces to teach coding to young children. The report by Papert and Solomon [24] also mentions a tangible implementation of the virtual turtle – inspired by Grey Walter's cybernetics animal – a robotic turtle that could draw shapes on the floor. Contemporary coding bots can be considered modern instantiations of these ideas.

While consensus has yet to be reached on a definition of CT for early childhood [9], researchers and educators are working to design evidence-driven interventions that foster knowledge and skills relevant to engaging in computational tasks. Most of this research is descriptive and provides a process account of learning. Few studies have examined the nature of learning involved when children engage with tangible robot toys, particularly from a cognitive perspective.

In this paper, we propose a motor-control-based characterization of CT, drawing on cognitive neuroscience studies. Based on the idea of tool incorporation, we propose an account of the mechanism behind the development of CT through participation in screen-free tasks. Incorporation has been used as a productive mechanism to understand learning in several studies [7, 26, 31]. In the present study, we propose an extension of the physical incorporation account to symbol-based incorporation, in the context of CT tasks. We re-characterize development of CT through screen-free tasks during early childhood as learning *symbol-based control*. Though preliminary, the proposal advances the research in this area and initiates conversations on extending the understanding of CT as well as the design of theoretically grounded interventions that augment practice-based design intuitions.

Why is such a theoretical approach appropriate? First, our participants are in kindergarten, where sensorimotor abilities are dominant, as compared with symbol-based abilities. Any theoretical account for this population would thus need to start from the sensorimotor system. Second, the task we use, based on a robotic toy, seeks to reconfigure participants' sensorimotor experiences using the toy, to foster a form of symbol-based control of the toy. Since the primary task (with the toy) is embodied and sensorimotor in nature, we need a theoretical model that accounts for the way embodied action could evolve into symbol-based control. Third, the programming task in the given context (and also more generally) can be understood as a control problem, where the behavior of a complex machine (the robot in this case) is controlled using symbols. A theoretical account of the way young participants' sensorimotor control skills could evolve into CT – through artifact control – would provide a general framework to model the way young learners transition to CT. Such a model would allow learning of CT to be understood as an artifact-mediated adaptation of an embodied skill, similar to the way recent embodied interaction systems seek to support the learning of mathematical concepts through sensorimotor interactions [2, 3, 30]. Such an embodied learning account – connecting sensorimotor control, artifact control, and CT – would help integrate CT with existing embodied approaches to mathematics learning.

2 THEORETICAL MODEL

We provide a cognitive account of the nature of CT, as it emerges in the activity of young children exploring a robotics-based coding-toy. We propose '*tool incorporation*,' borrowed from cognitive neuroscience studies that investigate the nature of Embodied Cognition (EC), as a candidate cognitive mechanism to understand learners' transition to CT. The next section introduces this theoretical model.

2.1 Tool incorporation: An introduction

Tool incorporation is a cognitive neuroscience model that has garnered much empirical evidence in the last two decades. The hypothesis suggests that intentional action with a tool extends a user's body schema. More technically speaking, it extends the user's *peripersonal space (PPS),* or the 'actionable' space immediately surrounding the user. Canzoneri et al. [4] describe PPS as "a portion of space immediately surrounding the body (near space), where external objects are located with respect to body parts, as compared to the far space." A review by di Pellegrino & Làdavas [25] reveals how the brain links somatosensory information from our body to signals (both visual and auditory) arising from objects in the space immediately around the body (PPS), and how this linking plays a role in sensory guidance of motor behavior. PPS extension during tool use is synonymous with the tool being incorporated into the body (See [22]). In other words, the tool becomes an extension of the user's body schema. This extension of the body schema expands the range of actions the user can engage in, thereby, expanding the space of possible actions (action space) surrounding the user. Importantly, tool incorporation not only extends the action space, it also expands the user's ability to imagine new actions. Due to this extension of both action and imagination spaces, the cognitive capabilities of the user, particularly related to possible actions, are also enhanced [5, 6].

The next section describes several empirical studies that illustrate tool incorporation. The first study examines tool incorporation of a physical object, the second study shows virtual incorporation, and the third study shows virtual tool incorporation. We unpack each of these studies in greater detail below.

2.2 Physical tool incorporation

The first influential empirical study to demonstrate tool incorporation was conducted by Iriki et al. [18]. In this study, the researchers investigated the neuronal firing pattern before and after a monkey learned to use a rake to obtain food.

This investigation was done in three phases (See Figure 1 *left* A-C). In Figure 1A, a light was flashed near the hands of a monkey and the firing of a bimodal neuron (coding for both touch and visual stimulus) was recorded. Next, as shown in Figure 1B, the monkey passively held a rake, and the light was then flashed near the hands, and also at the end of the rake. Neuronal firing was only observed when the light was flashed near the hands of the monkey. In the next step (Figure 1C), the monkey used the rake to reach food on the table that was otherwise out of reach. After this intentional reaching action, the light was again flashed near the hand and also at the tip of the rake. In this case, neuronal firing was observed in response to both flashes.

The researchers proposed that the change in the firing pattern before and after learning to use the rake indicates that the intentional action extended the PPS (see Figure 1D), to include the entire area within the reach of the hand and rake combined (Figure 1E). This indicates that the monkey's body schema had 'incorporated' the rake.

The nature of this extension is important, as incorporation consists not just of adding external entities to one's body schema, but "incorporation expands the range of possible actions the monkey

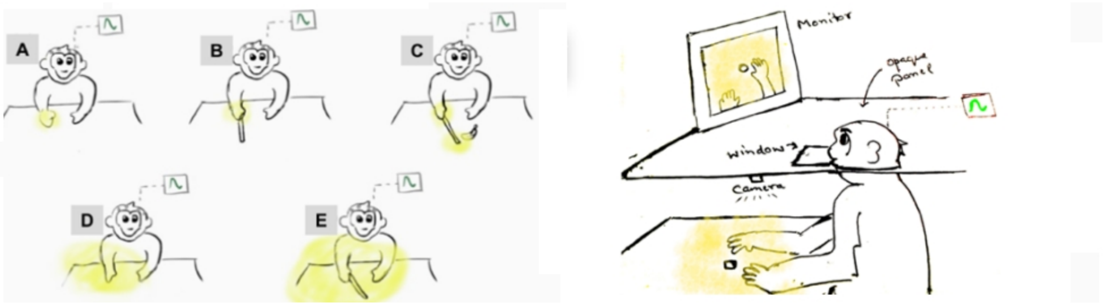

Figure 1: (Left) Tool use extends the body schema and the peripersonal space (PPS). (Right) Virtual Incorporation - Body schema extends to incorporate hand image and space around the monitor. Figures based on [22].

can do, and imagine — in terms of the location of the activity, other entities involved, the nature of the activity, the number of activities, and the permutations and combinations of activities" [31]. Thus, the expansion extends the monkey's understanding of the rake's uses as well as the spatial knowledge of the surrounding area in relation to the rake, indicating that the monkey's cognitive capacities and problem-solving abilities have been expanded. Other studies have reported similar incorporation accounts in humans as well [11].

2.3 Virtual incorporation

When playing video games, the self-image projected on the screen is designed to feel like it is part of – or an extension of – the user. Iriki et al. [19] investigated the neuronal mechanism corresponding with this experience of self-image in monkeys. Similar to their previous study [18] (discussed above), they trained monkeys to retrieve food, however, this time they designed the experiment in such a way that the monkeys could only observe their hand and arm movements via a real-time video monitor or by viewing these through a window cut out of an opaque panel obstructing the monkey's view of the table (See Figure 1 right). They found that the bimodal neurons in the intraparietal cortex fired when the monkey used this decoupled tool (decoupled in the sense that the feedback is from a screen and not viewed directly) to retrieve food. In their previous study [18], these neurons encoded the schema for the monkey's hand and had shown plasticity when the monkey used the rake to perform a goal-directed action. This study extended the incorporation account, by showing that the bimodal neurons code for the hand image on the screen as well, indicating that the image of the monkey's hands on the screen acts like an extension of the self. This result showed that incorporation can happen virtually.

2.4 Virtual tool incorporation

Extending these results, studies show that tool incorporation can also occur when the action space is a screen, rather than the physical world. In other words, *virtual tools* can also be incorporated into the body schema. Learning to use a computer mouse is an example of learning to control a virtual tool acting in a screen space, using a physical controller (the mouse). A mouse is a *decoupled* tool that controls cursor movement on the screen. The movement of the mouse in the physical world is continuously coordinated with the cursor's movement on the screen, even though the representation of the cursor is different from the mouse. Integrating the concepts of tool incorporation and virtual incorporation, studies have examined the phenomenon of virtual tool incorporation. For example, Gozli and Brown [13] examined the role of visuomotor control in the extension of PPS to the computer screen. In this study, the user's PPS extends to the cursor and the space on the screen, thus incorporating the tool virtually.

Learning to control a mouse can be considered a case of *physically decoupled* tool incorporation. The tool incorporation has a decoupled nature because the action space is discontinuous – it is distributed among two disconnected worlds: the controller action space (i.e., mouse movement in the world) and the virtual tool/object action space (i.e., cursor motion on the screen). The key thing to note here is that incorporation can occur across these disconnected worlds. Importantly, in the case of the mouse-cursor example, the feedback is continuous – in other words, the action effects are coupled or connected in time. Continuous and systematic feedback is the basis for the incorporation, even in this decoupled case.

2.5 Incorporation and discontinuity

One may ask, what are the features of the task environment that support the incorporation process? In the previous examples (a monkey using a stick to retrieve food, a monkey using the image of their hand on a real-time video monitor to retrieve food, humans learning to control a mouse), we can see that the tool user receives continuous perceptual feedback while engaging in the action. For instance, in the case of virtual incorporation, the monkey is constantly receiving visual feedback of the image of their hand in relation to the motion of their hand. Achieving coordination is difficult in this case, because of the *spatial discontinuity.* We define a spatial discontinuity as a difference in reference frames (e.g., the hand on the table vs. the hand image on screen). In the case of humans learning to use a mouse, the cursor position updates on the screen in relation to the movement of the mouse without detectable delay, and feedback is therefore continuous. However, learning to control the mouse is difficult, because in addition to a spatial discontinuity, there is also a *representational discontinuity.* The mouse does not resemble the cursor, though the spatial mapping of the mouse movement is proportional (but not exact) to the cursor movement on the screen. Another way to think of this is learning to use the trackpad, where the finger movements map to the cursor. In this case, however, the fingertip itself acts like the extension of the cursor, although there is no physical tool (such as a mouse). This example is closer to the monkey's case of virtual incorporation. The trackpad renders the fingertip as a virtual tool on the screen that users learn to manipulate and control. Here also feedback is continuous. However, there is a spatial and representational disconnect between the finger movement and the cursor, as the movement on the trackpad doesn't directly resemble or scale to movement on the screen. Given these cases, we propose the following three discontinuities that can make tool incorporation challenging:

- Spatial Discontinuity: When the physical continuity between the user and the tool is broken. Learning to use the stick is an example where there is spatial continuity between the tool and the body. Learning to use a virtual tool like a cursor with a mouse is an example of learning to control an entity that is physically separated from the body. Another example of spatial discontinuity would be the control of a toy car using a wireless remote control. The spatially decoupled nature of each of these systems leads to spatial discontinuity.
- Representational Discontinuity: When the tool, or the actions with the tool, do not resemble the entity, or the behavior of the entity, being controlled. In the case of the mouse, the representation of the cursor on the screen is different from the mouse being used. The representationally decoupled nature of this system leads to representational discontinuity.
- Temporal Discontinuity: When there is a lag in feedback between the action and outcome. In the above cases, we saw that the feedback was instantaneous, which is crucial for incorporation to occur. If there is a delay in feedback, the continuity is broken, which makes incorporation challenging. In the case of a programmable robot, there is a lag between building the instructions and then seeing the resulting movement of the robot, when the instructions are run. The temporally decoupled nature of this system leads to temporal discontinuity.

These three discontinuities can come with different levels of complexity. For instance, the controller actions could involve many buttons, and the response space (the screen) could show different responses to different button presses. In this case, there is complexity in both the spatial and representational discontinuities. Juggling is an example of a task where there can be different levels of temporal discontinuities, between throwing and catching actions.

3 BRIDGING THE GAPS: EPISTEMIC AND PEDAGOGICAL MOVES

The nature of the task environment and how the task is instantiated will impact the incorporation process. In the case of discontinuities embedded in the task space, learners are likely to enact different moves to coordinate and control the different discontinuous elements in the problem-solving space. The moves help bridge the gaps resulting from the discontinuities. This process allows the learner to move from limited and scattered incorporation to coherent incorporation. Moves enacted by learners and teachers in the context of a guided task can be characterized as *epistemic* and *pedagogical* moves, respectively.

Epistemic moves are spontaneous moves made by users to gain a better handle on the problem, leading to an increase in task performance, without changing the state of the task space. These moves are thus similar to epistemic actions [20, 21]. These moves play a key role in extending the action space and thus support tool incorporation. This role is indicated in a study [26] that characterized different epistemic moves made by students while solving an area task that involved manipulating tangible blocks. Pedagogical moves are the spontaneous moves enacted by a facilitator to scaffold a lesson/task objective to support students' thinking (For examples, see [12, 27]).

4 CHARACTERIZING CT AS SYMBOL-BASED CONTROL

We propose that the CT learned during our screen-free task can be characterized as learning of *symbol-based control,* through the context of the task (described in the next section). Incorporation acts as the mediating functional and neuronal mechanism that facilitates the development of this control. To support our proposal, we draw on the analysis of video data from a larger empirical study aimed at fostering CT in kindergarten children through the use of screen-free tangible coding toys. Our analysis is aimed at understanding what kind of moves were made by the participants during their exploration of the tangible coding tasks and how those moves may support the incorporation process.

Specifically, we investigate the following questions:

- What epistemic moves are made by the learners to gain symbol-based control?
- What pedagogical moves are made by facilitators to support learners in their efforts to gain symbol-based control?
- How might these moves foster the development of symbol-based control?

5 CT STUDY

5.1 Context

Three sessions involving Cubetto (a tangible coding robot toy) were introduced to four participants (ages 5 and 6), who came from a kindergarten in the rural Intermountain West of the United States. Each of the Cubetto sessions lasted 30 minutes. The sessions were recorded using a video camera. After the completion of coding lessons, a standardized summative assessment (~15 min) designed for the larger project (See [9]) was administered. The sessions and assessment were facilitated by a member of the research team with early childhood teaching experience.

5.2 Methodology

The data sources include, (i) video recording of the sessions (ii) video transcripts and content logs (iii) analytic memos generated during the data analysis. The transcript was analyzed using a fine-grained qualitative approach, with the help of Taguette, an open-source qualitative analysis software. For this paper, we share illustrative vignettes from a subset of video data from Session 1, in which four students (John, Isaac, Joanna, Eric) and their facilitator Mr. K were engaged in exploring Cubetto for 30 minutes. The group also had a prior three-session exposure to another robotics toy system - Botley.

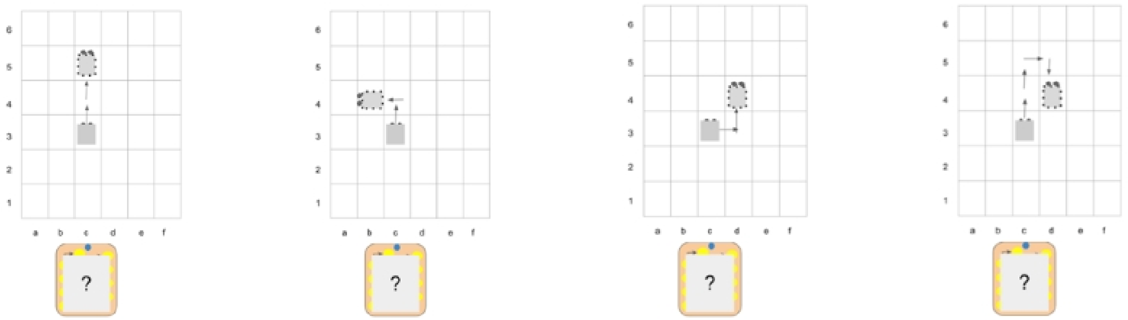

Figure 2: (L-R): Target tile sequence required to replicate the path - Task 1 (FF); Task 2 (FLF); Task 3 (RFLF); Task 4 (FFRFLB).

Table 1: Different tasks introduced in the 1st session of Cubetto

Activity	Description
Introduction to tiles (F-forward [green tile], B-backward [purple tile], L-left [yellow tile], R-right [red tile]);	Students predicted and observed the Cubetto move using individual tiles with different starting positions and orientations. Students enacted the moves forward, backward, left turn, and right turn with their own bodies.
Task 1-4: Replicating the path of another Cubetto system when the program is hidden. Students can watch the other Cubetto trace the requisite path and then try out tile combinations with their Cubetto system.	Task 1: Make their Cubetto go from square c3-c5; Task 2: Make their Cubetto go from square c3-b4; Task 3: Make their Cubetto go from square c3-d4; Task 4: Make their Cubetto go from square c3-d4 via a different path compared to Task 2 (See Figure 2).

Experience with Botley may have influenced their performance in the Cubetto task. Our goal in this paper is to introduce, unpack, and illustrate our theoretical model of CT and to characterize the different epistemic moves that may support incorporation in this context. In choosing between Cubetto and Botley, we focused on the Cubetto sessions due to the simplicity of the interface. We plan to extend this work by taking into account the continuum of experience across all the sessions.

5.3 Cubetto: Tangible screen-free coding toy

Cubetto is a robotic coding toy that moves on a grid in response to tactile tiles, which are placed on a standalone controller interface. The tiles are colored to represent movement, including forward (green), backward (purple), left rotate by 90 degrees (yellow), and right rotate by 90 degrees (red). Cubetto is simple in appearance. It is a small wooden cube with a face that indicates orientation. Each of these individual coding tiles makes Cubetto move based on its position and orientation on the grid i.e. where the Cubetto is currently and in which direction it is pointing.

5.4 Session overview

In the first session, the facilitator (Mr. K) introduces the Cubetto and how it moves on the action grid (grid map) by arranging the tiles in the controller grid. The session involves a combination of guided activity along with exploration of Cubetto while attempting four coding tasks. (See Table 1 for the summary).

6 CUBETTO SYSTEM AS A HIGHLY DISCONTINUOUS COMPUTER MOUSE

From an embodied learning standpoint, the Cubetto system ([action grid + robot] + [controller grid + tiles]) can be considered as a highly discontinuous computer mouse (Figure 3 left). The Cubetto task requires learning to control the robot movements using a sequence of colored tiles on a controller grid, which make the robot move on an action grid, to complete a task. We contend that learning to program the robot by placing the tiles in the controller grid requires, and leads to, incorporation of the Cubetto system ([action grid + robot] + [controller grid + tiles]) into the body schema (See Figure 3 right). This process is challenging, because the tool incorporation must occur despite three discontinuities: spatial, temporal, and symbolic.

To account for how motor control could be achieved despite these complex discontinuities, we relate the Cubetto task to the case of learning to use a mouse to control the movement of a cursor on a screen, which involves coordinating one kind of discontinuity. In this analogy, the controller grid and tiles are the equivalent of the mouse, and the robot’s movement on the action grid is the equivalent of the cursor. Interactions with the controller grid (arranging tiles) lead to systematic movements of the robot in the action grid, and thus gaining control of the robot’s behavior in the action grid. The symbolic ‘standing-in’ role of the tiles creates a representational discontinuity. The time difference in the arrangement of the tiles in the controller grid followed by the robot movements generates a temporal discontinuity. The spatial disconnect between the controller grid and tiles, and between (controller grid + tiles)

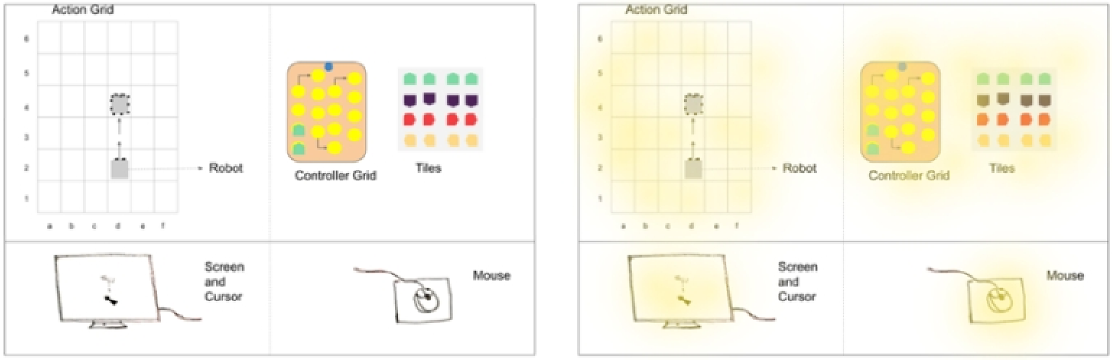

Figure 3: (Left) Cubetto system as analogous to discontinuous mouse. (Right) Incorporation of Cubetto system.

and the robot, creates a spatial discontinuity. Since both controller-based actions and its associated world changes are discontinuous, the required motor control of the robot can be achieved only by coordinating and integrating the different discontinuous elements, to achieve a stable and coherent interaction pattern. The motor control gained through this process is different from the continuous feedback case, as this task requires achieving motor control in a segmented fashion, based on many types of trials and many possible action-feedback configurations (different discontinuous steps in the controller board grid and their associated responses by the robot in the world grid). To distinguish this segmented case from the previous smooth action-feedback cases, we term this new form of motor control "punctuated" motor control. Figure 3 *right* shows the extension of the user's PPS in both cases – the Cubetto and the computer mouse.

The extended process of gaining this new type of motor control also generates a new type of punctuated action space, extending the body schema. This schema structure allows new kinds of discontinuous actions to be planned, based on this internalized action space. Importantly, once the punctuated motor control is achieved (and thus the Cubetto system is incorporated into the body schema) through real-time interactions, the resulting new body schema allows running 'offline' mental simulations of possible actions in the punctuated action space that is internalized. Different configurations of the controller and world states could be tried out virtually in this internal action space. This internalized body-schema-based process can be considered a form of embodied thinking, as the new body schema that developed through controlling the physical system is reused for running the mental simulations. In this account, control and incorporation are the critical processes that transform 'embodied doing' in a task into 'thinking'.

Extending this view to the task in our study, the CT gained through the Cubetto task is the ability to run mental simulations of possible robot movements, based on the new punctuated action space that is internalized. As this action space is *constituted* through multiple trials, mistakes, and backtracking, these debugging elements are also part of the action space, and thus available for simulation. Note that the possible movements in the internal action space is not limited to the ones learned during the task, as the affordances of this internal space, and the possible actions there, can be different from the physical one. Specifically, this space provides more opportunities to extend the task space itself. For instance, the learner could simulate a space where the robot can move diagonally, or a space where there is another robot controlled by a second player. Such 'counterfactual' possibilities make the internal action space generative, in ways that are different from the physical action space.

Given this theoretical view, we were curious what kind of actions children engaged in to overcome the difficulty involved in controlling the Cubetto system. Phrased in terms of our theoretical model, we were interested in understanding which moves (epistemic and pedagogical) helped children incorporate the Cubetto system into their body schema, thus extending their PPS to the controller grid, robot movements, and the tiles. Note that the tiles function as a type of dual-nature 'pushmi-pullyu' symbols [23] in this case, as they work simultaneously as control elements and standing-in elements.

As discussed earlier, the nature of the task environment makes incorporation challenging, and we would expect participants and facilitators to engage in interactional moves (spontaneous epistemic and pedagogical moves) to achieve motor control over the dual-nature symbols, enabling the transition to 'programming' Cubetto's movement. For this paper, we present illustrative instances from the interactions during Session 1 that have likely made the incorporation process smooth (i.e. facilitated bridging the discontinuities outlined earlier). We then provide an account of some of those interactions from the perspective of the incorporation model.

7 BRIDGING THE DISCONTINUITIES

Which moves (both epistemic and pedagogical) likely lead to establishing the coordination and integration of discontinuous elements? How do the moves foster incorporation based on our model? What is the role of the grid in establishing such coordination? In this section, we explore these questions, with examples from the CT task.

7.1 Epistemic move

Here is one example of an epistemic move we call an *epistemic gesture,* which emerged during the exploratory phase of the Cubetto:

> Scene (03:25-03:56): *After introducing green (forward one step) and purple (back one step) tiles independently, Mr. K (the facilitator) now layers the Green and Purple tile together and then asks both Joanna and John to predict how Cubetto will move. Then, Mr. K points his finger*

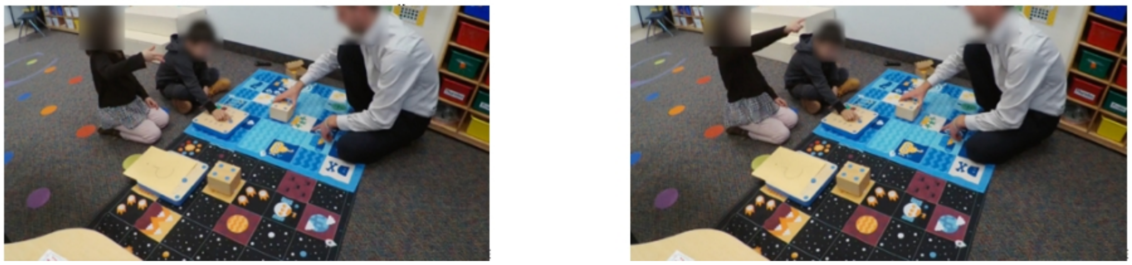

Figure 4: (Left) Joanna rotating her wrist clockwise and anticlockwise. (Right) Joanna moving her arms in a forward-backward motion.

> *to the green tile and then to the red tile, simultaneously saying "one square forward and one square backward". At the moment that Mr. K was describing the tiles and corresponding motion, Joanna starts to rotate her wrist clockwise and anticlockwise repeatedly (Figure* 4 *left). Then, Mr. K moved Cubetto manually, forward, and backward to show how it might move. Noticing this, Joanna instead of rotating her wrist starts to move her arms rapidly in a forward-backward motion (Figure* 4 *right).*

7.1.1 Cognitive characterization of the move. Joanna's wrist rotation and her hand movements can be considered non-verbal actions to help her to establish the coordination between the controller + action grid system with her bodily movements. This resemblance of the gesture (forward-backward motion) to the corresponding movement of the robot and the feedback from the facilitator is an example of how the spatial, representational, and temporal discontinuities are coordinated or bridged (to some extent) simultaneously, to support the incorporation process.

It is important to note that we are not saying that one isolated gesture leads to incorporation. This is because actions and control are multi-level integration processes, which can only be *modulated* by individual sensorimotor elements. Our ongoing work is focused on noticing the different moves that emerged in the task, which are likely to support the incorporation process. Providing a microgenetic account of the incorporation process is an eventual goal.

7.2 Pedagogical move

Below is an example of a pedagogical move that the facilitator introduced during the exploratory phase of introducing Cubetto:

> Scene (07:00-08:40): *Mr. K (facilitator) introduces the red piece (for right rotation). Before showing how the tiles work with Cubetto, he invites the group for another intermediate activity. He requests everyone to stand and take a step back. Next, Mr. K asks if the group recalls what the green tile signifies. After this brief interaction, Mr. K explains the activity to the group where they have to move based on the tile drawn. He starts with green (forward) and purple (backward) tiles. Mr. K draws one of these tiles randomly from the box, and the group attempts to enact the movement in sync with what the tile signifies (i.e., taking a step forward or backward based on where they were standing) (Figure* 5 *left). Next, Mr. K draws the red tile, and asks (08:19)"Guess what this piece does? It makes you go like this, watch it!" Mr. K stands and then turns 90 degrees towards his right. Mr. K shows the left rotation with the yellow tile as well and then repeats the activity with both red (right rotate) and yellow (left rotate) tiles, drawing them randomly. The group enacts the respective spin motion with their body (Figure* 5 *right). After this, Mr. K transitions to showing Cubetto's movement using rotation tiles on the grid.*

7.2.1 Cognitive characterization of the move. Physically moving in response to the controller grid's structure may help the children coordinate the feedback relations between the state of the dual-nature symbols (the tiles) and their own bodily movements. Establishing this mapping effectively bridges the gap created by the representational discontinuity between the dual-nature symbols and robot actions. For this activity, Mr. K leverages sensorimotor experiences, in an implicit way, allowing the watching members to enact the forward-backward and rotation movements with their entire bodies. Possible variations of the activity could include gesture-based movements, like using the hands or head movements to indicate a left turn or right turn.

Our preliminary analysis indicates that the emergence of epistemic moves by learners, augmented by pedagogical moves by the facilitator, may play a significant role in achieving control over the toy, overcoming and bridging the gaps caused by the three discontinuities, and thus supporting the incorporation of the Cubetto system.

8 ASSESSMENT TASK AND RESULTS

Students took a summative assessment after participating in the coding lessons. While the coding lessons were taught using Cubetto and Botley, the assessment tasks were not bound to a specific coding toy; they were unplugged and "toy-free". The assessment materials included 10"x10" paper grids, agents (i.e., small plastic bugs), four directional arrows (forward, backward, rotate right, rotate left), code strips (programs to either debug or enact), and a program organizer on which the students could place their written sequences (See Figure 6). The tasks involved storylines around moving an agent from one location to another (e.g., moving the beetle to the grass

Figure 5: (Left) Group attempts to move forward (green tile) or backward (purple tile) based on the drawn tile. (Right) Group attempts to rotate left (yellow tile) or right (red tile) based on the drawn tile.

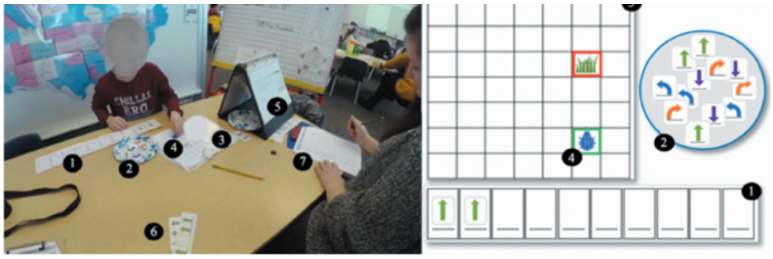

Figure 6: Unplugged CT Assessment. Left shows materials used in assessment tasks: (1) program organizer (2) arrow codes (3) grid pages, administration flip book (4) moveable agent (5) administration pages, with script (6) preset code strips (7) scoring sheets. Right shows child's-eye view of assessment materials. Image Credits: [9].

patch on the grid). Specifically, they were asked to write a sequence of codes, enact programs, identify a bug in a program, fix buggy programs, and identify what a specific arrow would make the agent do. There were 26 items in total in the assessment. Some tasks had only one possible correct answer, whereas other tasks had multiple correct answers. The administration of the assessment was standardized. Two raters double scored the assessment. For more information on the assessment, see [9].

Learners were able to perform well in the assessment task. (Out of possible 26 points, John got 19, Eric got 18, Joanna got 19, Isaac got 16.) The results from the assessment task, where children were asked to generate robot states using configurations of the dual-nature symbols in a *static* grid (an abstract instantiation of the dynamic Cubetto system), indicates that learners have developed an internal action space. Note that the dual-nature symbols function more as standing-in structures in the internal space, given the static nature of the task.

We suggest that this performance on the assessment task indicates that the children gained control over the discontinuous Cubetto system (Controller + Action Grid), and thus successfully incorporated the system into their body schema. This is because mentally simulating the states of the tiles and its effects on the robot requires fully incorporating the Cubetto system, which, in turn, requires coordinating and integrating all the elements in the task space, through feedback. It is the revised body schema and action space that results from the incorporation that allows learners to smoothly run "offline" simulations (imagination) of the task.

This imagination process would be difficult to execute if the controller grid and the robot world were not fully incorporated, as the possible action space in this case would be a patchy one, where the controller and the world are not fully coordinated and integrated. Incorporation thus allows learners to reenact the embodied dynamic task covertly, in a coordinated fashion, when presented with the static task. This capacity to control the robot system, using 'virtual' movements in a revised action space, can be considered the beginnings of CT.

9 DISCUSSION

The incorporation account of CT we outline here is preliminary, but it provides a new way to characterize learners' transition from a dynamic embodied task to a thinking task. Since this characterization is based on a well-established cognitive mechanism and related experimental studies, it provides a starting point to develop empirically testable theoretical constructs for analyzing embodied learning. These constructs could lead to novel motor-control-based design approaches that help support model-based reasoning and thinking.

Extending our theoretical account, it appears that a cluster of features – grid structures, control based on highly discontinuous elements, and testing based on static systems – might be a recurring general pattern in learning designs and tasks where participants transition from embodied interactions to thinking. Versions of this cluster seem to be part of other motor-control-based approaches to learn abstract skills, such as the use of a mental abacus for calculations [8, 15, 16], learning the area concept using manipulatives [26], learning of proportions [1], and learning physics using mixed reality [10]. More broadly, our account also provides a new way to think about the nature of symbols from an embodied cognition standpoint – as punctuated/serrated/segmented control structures, which can be activated and recombined virtually, to generate novel action spaces.

This view makes the incorporation account a general theoretical model, which might make possible theory-driven approaches to design novel dynamic and embodied tasks that advance the learning of model-based reasoning skills, particularly the set of skills enacted in CT. For instance, designers interested in extending the Cubetto system to include advanced logic and signal processing could use the constructs of punctuated control, incorporation, and the epistemic/pedagogic moves to generate and analyze candidate designs and choose between them. The incorporation model might also provide ways to develop new teacher-training approaches that allow teachers to promote embodied learning of model-based thinking and reasoning.

From the standpoint of embodied cognition theory, the incorporation account suggests that every embodied learning event changes the body schema, and the body's functional capabilities. These revised capabilities can be characterized from both a motor control standpoint and an internal schema (neural network) standpoint, suggesting that these two types of theoretical accounts of learning can possibly be reconciled, as they both refer to the same dynamic and interactive system that is constantly transitioning towards more complex action spaces. Finally, we note that our account extends the incorporation model itself significantly, to cases with high levels of discontinuity, symbolic elements, and abstract thinking. If empirical studies support this model, this work would contribute back to basic research, thus forming a productive loop between educational applications and basic research.

10 CONCLUSION

In this paper, we proposed a motor control-based characterization of a CT task, where a group of kindergarteners and a facilitator engaged with Cubetto, a screen-free tactile coding robot. We drew on the "tool incorporation" mechanism from cognitive and motor neuroscience studies to propose a theoretical account of how CT developed from this embodied task. We characterized the CT task space as analogous to a highly discontinuous computer mouse, with three key discontinuities (temporal, spatial, and representational). This structure makes the task challenging for learners. We hypothesized that children and facilitators must engage in spontaneous moves (epistemic and pedagogical) to bridge these discontinuities and gain control of the system. To ground this theoretical proposal, we examined video data of one of the three teaching sessions with Cubetto, and noticed instances of both an epistemic move and a pedagogical move. We characterize these moves based on the model. The incorporation account, based on the case of Cubetto (an instance of embodied task), presents a mechanism model of how embodied 'doing' becomes 'thinking'. We discuss some broader implications of the model and ways it can be extended to both applied and basic research.

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