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Material Anchors for Young Children's Spatial Planning: Contextualizing Path-Program Relationships

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Abstract: Planning a path from an origin to a destination is a common task for studying children's spatial thinking and a foundational part of many early programming environments. This paper examines children's means of abstraction between the grid space and the program domain through an exploration of the strategies they used to plan a robot's routes in 2-D space. Qualitative analysis focused on ways children used materials to aid in spatial planning and programming, advancing previous work on material anchors for concepts (Hutchins, 2005). Through an elaboration of several path planning strategies, we illustrate how children varied in their use of materials in space to represent a path-program relationship. We argue that these strategies represent multiple ways of contextualizing and abstracting in a programming task, with implications for design of equitable CT assessments in early childhood.

Introduction

The material world is implicated in how we conceptualize spatial activities. For example, Hutchins (2005) theorized how a concept of "queuing" is informed by encountering the physical arrangement of bodies forming a line towards some destination; people learn to get in a queue by relating the conceptual space of the queue with its material referent. This complex interplay of conceptual notions and material setting presents questions about the role of concrete objects in dynamic spatial concepts, such as forming a line or following a path. Planning a path from an origin to a destination is a common task for studying children's spatial thinking and a foundational idea in programming environments frequently used in early childhood. For children who are still acquiring directional language like left and right, planning the steps of a route can be challenging. In addition, the symbolic system of navigational arrow codes can be confusing for children who are in the process of associating a wide variety of symbol systems with meanings and material structures (Clarke-Midura et al., 2019; Silvis et al., 2020). Verbalizing or visually representing instructions for another agent to move in sequential steps makes the task even more complex, as the child must engage in perspective taking and reconcile sometimes conflicting spatial orientations (Clarke-Midura et al., 2021; Flood et al., 2022). This paper presents research on children's materially-based strategies for path planning on a two-dimensional (2D) grid with a tangible agent (i.e., a robot) and manipulable directional arrow codes (see Figure 1).

The tasks were intentionally designed to observe children's thinking through their interactions with the materials. As children planned and programmed instructions for the agent, they manipulated arrows in different ways and demonstrated a range of strategies for conceptualizing a path-program relationship. For young children, planning routes involves tacking back and forth between a path and programming materials to anchor abstractions of space across physical and conceptual domains. Our findings highlight the critical role of material context in task design and implicate abstraction in spatial planning.

Contextualizing path planning

The relationship between material and ideational tools mediating human knowledge is an important pillar for situated theories of cognition, child development, language, and mathematical thinking. Hutchins (2005) referred to the "association of conceptual structure with material structure" as "a general and ancient human cognitive phenomenon" (p. 1555). Hutchins used the cultural practice of queuing to theorize how people learn to encode spatial relations to form concepts. He suggested that "in order to see a line as a queue, one must project conceptual structure onto the line" (p. 1559). Not all lines are queues, and not all queues are straight; in order to have a concept for a queue, one must turn line-like structures into a meaningful type of line, one that sequences bodies as they progress towards some location. What Hutchins called "material anchors" are the physical, material, (in our case) tangible objects used in bodily interactions with the physical world as part of the process of conceptual development. A question that Hutchins asked was "*Where* does queueing happen?" Does queueing happen in the conceptual space where the queue-concept takes shape and stabilizes, or in the world where the queuing body takes a place in line? At stake in this question is the role of concrete objects in forming spatial concepts.

This example was instructive for us as we examined the literature on children's development of route planning and spatial thinking. For example, Rogoff (1991) investigated 4- and 5-year-old children's development of route planning through guided participation in a task where children and parents planned a series of imaginary errands on gridded maps representing their neighborhoods and grocery stores. She found that it may be particularly difficult for young children to engage in abstract thinking about future events or anticipated spatial movements when these activities do not have "concrete, present referents" (p. 361). Sophisticated planning strategies involved marking map destinations with colors and symbols to facilitate planning the optimal route that *children themselves* could conceivably follow if they ran errands or navigated the grocery aisles. Similarly, in Hutchins' example, the queue represents a conceptual-material space that the queue-conceptualizer will use. Our tasks were different in that the planner was designing a route *for another agent*.

Providing instructions for another agent involves spatial perspective taking (Clarke-Midura et al., 2021) and draws on Papert's (1980) notion of "body syntonicity," or the ways children use a sense of body and self to learn abstract concepts like codes (Flood et al., 2022) or states of matter (Danish & Enyedy, 2020). Our work draws on the paradigm of LOGOs turtle geometry and tangible computing (Papert, 1980). The tasks described below situate abstract spatial movements in Cartesian space within a "program space" (Silvis et al., 2020). Children must make a series of associations between the abstract codes representing directional movement in the program space and the concrete physical path where movements happen on a grid. It is this relationship between physical space and abstract symbols that prompted us to consider a version of Hutchins' question: Where does the path happen? We use this theoretical question as a point of departure for asking: *How did materials help children represent their conceptual understanding of a path-program relationship in CT tasks?*

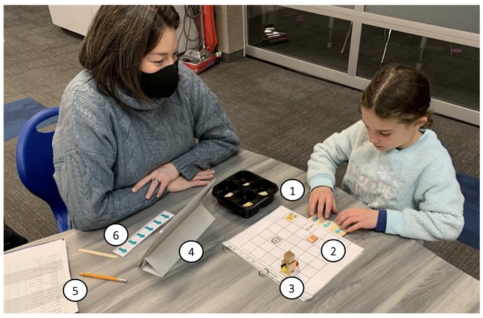
Study design and context

This analysis is part of a broader study in which we used Evidence Centered Design (ECD; Oliveri et al., 2019) to iteratively develop a CT assessment for kindergarten-age children that measures their ability to engage in CT practices (e.g., write or enact sequences of code, debug buggy programs). Materials include 2D 6x6 grids (Figure 1) that provided storyboards to situate the tasks, a small wooden agent/robot, and wooden tiles depicting four individual arrows: rotate right on a point (R), rotate left on a point (L), move forward one square (F), and move backward one square (B). Children were instructed to line up or sequence the directional codes in a row *underneath* the grid ("left to right like reading a book"). Despite this instruction and gentle reminders in-task, children developed a range of different strategies for sequencing arrows to build programs.

Participants, data, and analysis

We conducted qualitative analytic coding of video-recordings of children (N=272), ages 4-8, across five semi-rural elementary schools in the United States, as they engaged in CT assessment tasks (average length = 15 min). Assessments were standardized and administered one-on-one by members of the research team.

Figure 2
Materials used in CT tasks.



(1) box of 4 types of arrow codes
(2) storyboard grids
(3) wooden robot agent
(4) administration items/scripts
(5) observational record sheet
(6) pre-set programs

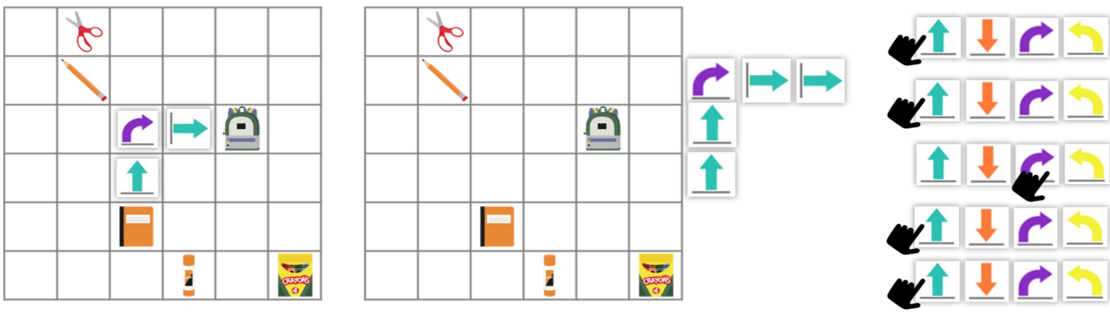
Prior to the current analysis, we conducted a round of coding, where we established a preliminary analytic code system for children's programming strategies, including how they used materials during tasks, how they used movement and gesture while coding, and how they verbalized program planning. Starting with this *a priori* code system, two research assistants coded the majority of the assessment events (83 hours of video). First, they open-coded a subset of the video, adding to the *a priori* codes and reducing redundant codes. The research team met weekly to establish agreement for strategies that were unclear or were hard to determine from the video record. We reached saturation with descriptive codes after coding approximately 50 assessments.

Then both research assistants coded approximately 100 students, to refine the strategy code definitions. One theme that cut across categories involved *children's path planning*: how children were using materials, their bodies, and spatial language to plan the robot's routes during tasks. We focus on several forms of path planning selected because they represent both common and uncommon material-based strategies and because they speak to our larger theoretical question about the "where" of path planning.

Findings

Some children placed the arrows on each grid square. Others assembled the arrows in the shape of the path off the grid. Some stacked arrows in a tower vertically, while others placed arrows in random, nonlinear positions on the table. Children also interpreted path planning creatively, sequencing instructions that sent the robot "elsewhere" to a destination image on the grid, even when the task did not specify a destination. We illustrate three of these strategies: *mapping symbols onto spaces*; *path-shaping off-grid*; and *remotely planning a path*.

Figure 2
The Notebook Task, Robot travels from notebook to land on backpack. (Left) mapping symbols onto space; (Middle) path-shaping off-grid; (Right) remote path planning.



Mapping symbols onto space

Program and path planning involves conceptually mapping a correspondence between the symbolic meanings of the directional codes and the material movements of the agent in physical space. For many children, mapping this correspondence meant placing codes directly on the map or grid-space. Children using the grid as a programming space allocated one code per grid square, creating a path-shaped program on the grid. This strategy was frequent in the Notebook Task (Figure 2), where children were asked to write a program for the robot to travel from the notebook to the backpack. The correct path was FFRFF. Because the rotation code just reorients the agent, children placing codes on the grid often undercounted their codes, producing FRF.

Path-shaping off-grid

Some children sequenced their codes spatially in the *path shape*, or what we call off-grid "path-shaping" with codes. As with programming on-grid, the Notebook Task served as a useful task to make off-grid path-shaping observable (see Figure 2). Children who performed path-shaping off-grid relocated the program from the grid space to an adjacent area on the table for path planning. This new context off-grid lacked the grid lines that had scaffolded reasoning about path-program-movement correspondence for on-grid programmers. However, the programs children assembled on the table in the shape of the path continued to resemble the grid.

Remotely planning a path

On-grid and off-grid path planning strategies described above represented alternatives to linear program sequencing. Less often, children declined to use the directional arrows to *build* programs altogether and took another approach to path planning. One radically different approach was to select one of each of the directional codes (even those not needed for a given task), place them on the table, and press them like buttons on a remote control to execute each code. Using this strategy to perform the Notebook Task, required tapping FORWARD twice, then ROTATE RIGHT, then another two FORWARD taps (Figure 2). Tangible sequencing that we had designed our assessment tasks to simulate, was instead associated with a different computational context (e.g., TV remotes, video game controllers), where remote controllers operate the machine. Remote paths did not take shape on the grid, nor did they materialize on the table in a path-shaped program. Rather, children planned paths in a remote space, where each movement was invisible, rather than a durable, manipulable sequence of codes.

Material anchors for CT assessment design

Path planning in tasks where an agent moves around a gridded space involves mapping a correspondence between at least two domains: the domain of the grid (path) and the domain of the arrow symbols (program). Children's use of the arrows indicated how they were understanding the relationship between these two domains. Their material strategies demonstrated how they abstracted from the immediate physical grid to the directional codes (mapping symbols onto space), from the grid-space to the program-space (path-shaping off-grid), and from directional codes to imagined movements (remote path planning). This series of abstractions allowed children—at different moments, in different items, and selectively employing different strategies—to traverse task contexts and bridge path-program concepts in ways that are important for emerging CT.

While we would not claim children were making huge leaps in abstraction characteristic of programmers who treat algorithms or problems as decontextualized objects (Hazzan, 2003), our CT tasks and materials elicited modest context-shifts that allowed children to move freely between levels of abstraction. Decontextualizing and recontextualizing problems is a critical part of abstraction and central to CT (Flood et al., 2022). Rather than progressive levels of abstraction—whereby children perform increasingly sophisticated forms of path planning from the grid, to the table, to the remote control— we prefer to see children's diverse strategies in terms of *varying degrees of material anchoring* (Hutchins, 2005). The various shapes their solutions took was another reminder for us, as designers, that an abstract, linear logic of programming is not inherent to computing, it is but one way of thinking computationally (Turkle & Papert, 1990). Even in a relatively constrained system of four directional arrow codes, children demonstrated a range of concrete strategies for approaching programming. Our findings are making us question the underlying rationale for prompting children to write linear algorithms for complex, dynamic paths. Particularly for preliterate children for whom "left to right like in a book," already involves abstract, arbitrary conventions, we want to incorporate multiple ways of using materials in our task models so that our assessments are accessible and equitable.

Acknowledgements

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