Embodiment of Computational Thinking During Collaborative Robotics Activity

Theodore J. (TJ) Kopcha, Ceren Ocak
tjkopcha@uga.edu, ceren.ocak@uga.edu
University of Georgia

Abstract: This case study explored how young children's thinking was embodied during collaborative robotics activity. Two 5th grade learners were recorded as they worked together to program and navigate a robot across a 3'x3' grid of obstacles. The video was then analyzed using a grounded theory approach (Glaser & Strauss, 1967) to determine how cognition manifested in an embodied manner (e.g., gesturing, use of conceptual metaphor) through the tools and affordances employed by the learners. Four primary tools were used by learners in solving their robotics task: (1) basic robot moves, (2) gestures, (3) the map and the computer, and (4), the grid and the robot. These tools provided symbolic access to direct experiences, supporting an emergent and reactive process in which perception and action were intimately linked. Implications for computer science and improving the design of computer-supported collaborative learning are discussed.

Introduction

Educators and policymakers currently are interested in integrating computer science into K-12 curriculum. At the heart of computer science is computational thinking, a problem-solving process in which both abstract and automated processes are involved in formulating problems and developing solutions during programming activity (Cuny et al, 2010; Wing, 2006). Learners who engage in computational thinking decompose the larger task into smaller subgoals, use algorithmic thinking and pattern recognition to create new and novel programs that address those subgoals, and debug programs that are not performing optimally (Yadav, Mayfield, Zhou, Hambrusch, & Korb, 2014). These skills are important for developing a competent 21st century workforce, making computational thinking in K-12 settings a critical and current issue (Israel, Pearson, Tapia, Wherfel, & Reese, 2015; Sengupta, Kinnebrew, Basu, Biswas, & Clark, 2013).

One way computational thinking and computer science are brought into K-12 classrooms is through robotics activities. Robotics creates an opportunity for learners to work collaboratively to program a robot and complete various tasks (Yuen et al., 2015). The physical nature of this activity is important. Robotics activity creates an opportunity for learners to make use of various tools and their affordances (e.g., the robot) to connect their abstract thinking with the environment. Thus, learners who engage in robotics activity are likely to experience an embodied experience, where mind, body, and environment are intimately connected (Gibson, 1979) in an effort to set and achieve specific goals with the robot.

However, little is known about how young children's thinking might be embodied during robotics activity. Research on computer science and programming is lacking from K-12 classrooms (Lye & Koh, 2014). Few if any studies of computational thinking examine the process through the lens of embodied cognition (Grover & Pea, 2013). Likewise, there is a need for empirical studies of young children who engage in robotics activity; early success with computer science through robotics has the potential to increase interest in and success with STEM outcomes in future coursework (Sullivan & Bers, 2016).

The purpose of this case study was to explore how young children's thinking was embodied during collaborative robotics activity. Two 5th grade learners were recorded as they worked collaboratively to program and navigate a robot across a 3'x3' grid of obstacles. The video was then analyzed using a grounded theory approach (Glaser & Strauss, 1967) to determine how cognition manifested in an embodied manner (e.g., gesturing, use of conceptual metaphor) through the tools and affordances employed by the learners. This study provides key insight into the ways that learners learn together through the help of digital technologies; examining computational thinking as an embodied phenomenon holds implications for collaborative robotics activities with young learners.

Overview of ecological embodiment in its implications for collaboration

Ecological perspective towards embodiment

Gibson's ecological psychology (1979) laid the foundation for our research. An ecological perspective towards embodiment suggests that the body serves as a mediator between perception and action; both perception and action are influenced by the environment (Gibson, 1977, 1979). From this perspective, thought is "a whole-body activity in context than simply an in-the-head process" (p.171). In other words, embodied cognition involves a complex relationship between the mind, body, and the environment. This stands in contrast with our understanding of information processing, where perception and action are treated "separately and sequentially" (Michaels & Palatinus, 2014, p.20). As argued by Richardson, Shockley, Fajen, Riley, and Turvey (2009), perception and action are mutual and act together to meet a particular goal. This suggests that thinking is a goal-directed reaction against what is perceived from the environment (Chemero, 2011, Michaels & Palatinus, 2014). In this paper, we draw on the basic premise of ecological psychology to explore children's thinking as a whole-body activity, where the environment guides their decision making.

Affordances

The concept of affordances is at the forefront of the ecological perspective. Affordances are conceptualized as opportunities or possibilities for action placed in the environment (Rietveld & Kiverstein, 2014). For example, "a flat horizontal surface affords standing and walking, a graspable rigid object affords throw" (Hirose, 2002, p.290). That being the case, the notion of affordance has been gaining prominence in different disciplines such as game design and development, computer science, and learning sciences (Harlow, Dwyer, Hansen, Iveland, & Franklin, 2018; Young, 2013). For instance, Linderoth (2012) used the perception of the affordances in the games and acting on them to understand the gameplay. Hammond (2010) examined the concept of affordance regarding its implications for the use of information and communications technology (ICT) in teaching and learning.

Tools can also serve as an affordance from the perspective of ecological embodiment. Liben (2002) explained how "tools are the functional extension of the environment, it has specific affordances and provides new opportunities for action" (p. 290). Tools can amplify perception to move beyond the physical capabilities of the body. In addition, tools provide opportunities for learners for "active material engagement" (Malafouris, 2013, p. 169). Therefore, the tools become an affordance as the user acts upon them. In this way, the tool and the user of the tool are often considered as a single unit of analysis (see Harlow et al., 2018). That is, the user and the tools become a compound element of a larger system in a cycle of perception and action.

Embodied collaboration and gestures

Physical gestures are considered strong evidence of embodied cognition (Alibali et al., 2014). Gestures also reveal the features of collaboration in that "gestural communication is based on a common conceptual ground, on the shared knowledge of what 'we both know together'" (Vasc & Ionescu, 2014, p. 150). Vasc and Ionescu (2014) further established that collaboration in a given medium has two sides: the receiver and the communicator; the receiver knows the meaning that a gesture carries and the communicator uses the gestures with confidence that the receiver would understand since it emerges out of a shared experience. That being the case, learners' gestures add another layer to understand how collaboration emerges as an embodied phenomenon as pairs of learners mutually act on the affordances they perceive. In this study, we therefore examine the way tools were used as affordances, and how gesturing supported learner's thinking as they engaged in collaborative problem solving during robotics activity.

Methods

The video data that was analyzed in this study was collected as part of a larger design research project that focused on developing and testing a robotics unit. The unit was designed as integrative STEM curriculum that supported computational thinking and embodied cognition during collaborative problem solving (see Kopcha et al., 2017). Six 5th grade teachers from a local school setting played an integral role in developing and testing the unit. The unit was enacted over a 2-week period, where learners worked in small groups to navigate a robot through a 3'x3' grid containing various obstacles. As part of the unit, learners explored science and math-related concepts that met specific state standards, including: constructive and destructive forces; operations with fractions; coordinate grid; and algebraic thinking.

Video of Learner activity was recorded in each of the six teacher's classrooms throughout the three class periods in which learners engaged in programming the robot (120 minutes total). Cameras were placed such that small group activity was recorded at both the computer (i.e., when programming) the robot as well as the grid where they executed their program. This provided data for fine-grained analysis of gesturing as well as evidence of the different forms of computational thinking (e.g., problem decomposition, debugging).

To investigate *embodied cognition during collaborative robotics activity*, we focused on the final 60-minute segment of video in which learners completed the majority of the robotics task. We reviewed the video data from each classroom and ultimately selected a single case to explore our research question. The case was a pair of 5th grade learners (one boy, one girl) who successfully completed the robotics activity. Using a single case allowed for an in-depth and fine-grained analysis of the how the learners used each tool and affordance to successfully complete the robotics task. It also allowed us to better understand the ways that various tools served as an affordance to support successful robotics activity as an embodied collaborative experience.

Instructional context

The robotics task was designed around the source-path-goal schema (Johnson, 2008). Learners were tasked with helping scientists use a robot to collect three samples from an active volcano. These three samples served as the checkpoints that the robot needed to visit in the overall task. Independent from the what path it followed, Learners were asked to program the robot to stop at each collection then arrive back to its original location. The pair then collaborated to determine an overarching solution path and the decompose the overarching task into smaller subunits.

The active volcano was represented on a 3-by-3-foot grid consisting of 36 six-inch squares. The three collection sites were scattered about the grid, along with a variety of elements associated with an active volcano (e.g., dust plume, flowing lava). Learners were challenged to maneuver the robot around the grid, avoiding the elements of the active volcano and visiting each of the three collection sites. The grid served as a testing site where learners practiced the codes that they wrote.

Computer-supported collaboration took place throughout the activity. Learners were put into pairs and tasked with breaking the task down into sub-goals, programming the robot, and accomplishing as much of the overall task as possible. They repeatedly moved between programming the robot at the computer and testing their programming at the grid (see Figure 2). With every attempt, learners continuously advanced and optimized their calculations to be able to move the robot in the coordinates of the grid precisely.

Figure 1. The visual block coding program (left) and the grid representing an active volcano (right).

Data analysis: A grounded approach

Knowing that gestures carry a semantic value (Alibali, 2005), we transcribed the video and audio data simultaneously for the selected case. Transcripts included the full conversation between learners, paired with short sequences of images from the video to illustrate specific gesturing and learner action. We then followed a grounded theory approach (Glaser & Strauss, 1967), employing an inductive data analysis process to generate our own theoretical understanding of the ways thinking was embodied during robotics activity. A grounded theory approach served the aims of this study because it results in identifying overall patterns that are grounded in data.

Data analysis started with open coding (Johnson & Parry, 2016). During open coding, we tried to be "stay close to the data" (Charmaz, 2006, p.49) by avoiding apriori theoretical presumptions that we had. Our initial codes included: tools/affordances, gestures, and semantics/verbal content. Tools/affordances included the objects in the environment that the learners drew upon as part of their collaborative problem solving, such as the map and the computer and the robot at the grid. Gestures were any hand or body movements made by the learners during collaborative work; this often took the form of imitating the movement of the robot. Semantics/content included specific aspects of note such as descriptions of specific gestures (e.g., learner uses hands to mimic wheels of robot turning right) or the meaning behind those gestures. These codes were broad enough to begin analysis while leaving room for new codes to emerge.

After the open coding, the researchers came together to identify a core variable from the initial codes that was also related to our inquiry. Our goal was to better understand the tools that were used as affordances by

learners and how their thinking was embodied with and through those tools. Our core variable was therefore the tools that learners drew upon during collaborative problem solving. After identifying our core variable, we returned to the transcripts to engage in selective coding and establish the relationship between the categories surrounding the core-variable (Johnson & Parry, 2016). Using the participants' own words to examine these relationships helped retain the essence of the mutual conversation and understand the affordances and semantic context that framed the gestures (Birks & Mills, 2011). This confirmed that the learners used four primary tools while solving their robotics task (Charmaz, 2006): the robot, the grid, the map and the computer.

Two additional coding categories emerged from this deeper analysis. First, we coded basic robot moves that the learners developed as part of a shared language during their problem solving, such as turning at a right angle and moving one unit square on the grid. Second, we coded specific gestures that also served as a fundamental tool for communicating problem solving. These two codes were strongly related in that the gestures used for problem solving often reflected basic robot moves. This served as an indicator that learners' thinking was distributed onto "external information bearing structures" (p.15) (e.g., hand motions indicating turns or unit movements) to articulate their underlying cognition and improve their problem-solving during computational thinking (Rowlands, 2010).

Findings

Four primary tools that the learners used while solving their robotics task were: (1) basic robot moves, (2) gestures, (3) the map and the computer, and (4), the grid and the robot. These tools illustrate the ways that thinking was embodied during their collaboration.

Tool 1: Basic robot moves

The learners began by establishing an overarching solution path. In this case, the overarching solution was to program the robot to visit the three collection sites without hitting the obstacles scattered in the grid (see Figure 2). The learners then formulated that path into two basic robot moves: (1) a unit square and (2) a 90-degree turn. The unit square was a move that traversed one of the squares on the grid. It was created explicitly by the pair to solve the problem; units could be combined to represent larger movements by the robot. In this way, these basic robot moves represented an abstraction of the 6x6 grid in that they represented a group of underlying algebraic thinking - moving one unit meant making the robot move at a specific speed for a specific amount of time. If two units were desired, the learners would double the time of associated with that speed. This increased the precision of their calculations while allowing them to work more effectively without repeated visits to the grid.
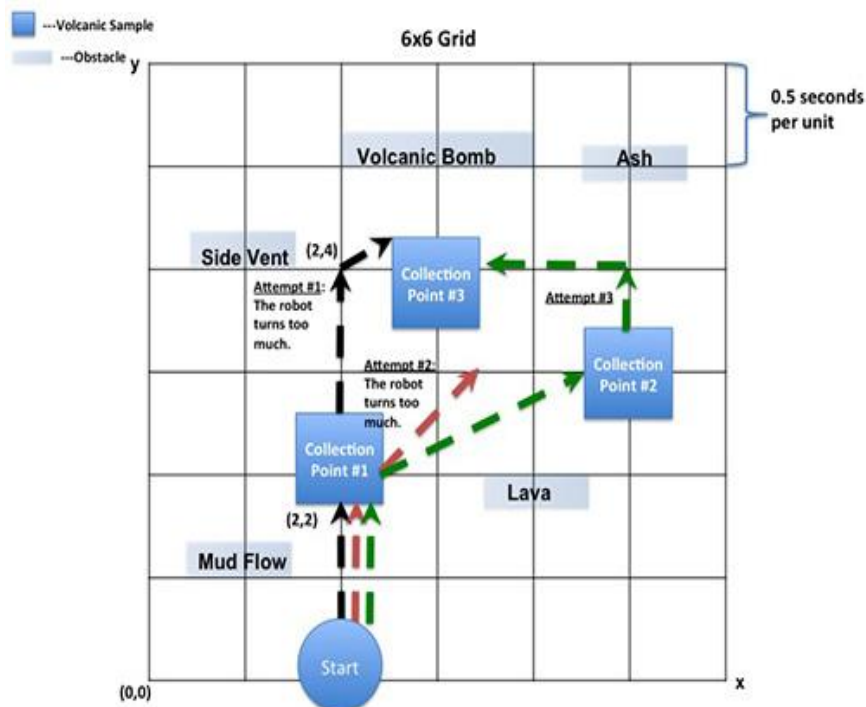

Figure 2. The dotted lines represent the learners' different attempts at completing the robotics tasks.

The 90-degree turn represented an abstraction of multiple underlying algebraic calculations, in the same way as the unit square functioned. To achieve the 90-degree turn, the pair needed to think about multiple variables at once – the relational speed of the wheels with one another as well as their turning direction and duration of the movement. Negotiating those variables led to the development of a shared language in which each of the basic moves (i.e., unit square and 90-degree turn) made collaborative problem solving more efficient and effective. For example, the learners repeatedly returned to the computer after testing a potential set of movements from the robot. Here, they re-enacted the robot's movements at the grid and constructed new movements to correct any problems with their solution path. They accomplished this by invoking these basic moves to articulate their thinking (e.g., "We need to go forward one, then turn right.")

Tool 2: Gestures

The findings from the data indicated that the emergent physical gestures supported learner's thinking as they engaged in collaborative problem solving during robotics activity. The gestures largely served as a re-enactment of the robot's movement at the grid. The gestures helped the learners gain the perspective of the robot, specifically when debugging the solution and reprogram the robot's movement. In this way, their gestures served as a tool for thinking through and communicating their ideas for combining basic moves into more complex movements (see Figure 3).

The most common combination of basic moves was moving straight and turning; this took place five times over the course of the entire solution path. As the learners collaboratively planned these combinations of basic moves, they employed several gestures to denote the movement of the robot. Figure 3, parts a, b, c, and d, display the gestures associated with this sequence of movements: "We stopped right there and we turned to the left [3a]. And now we need to go forward for one second at speed 5 [3b]." The boy then moves his hands apart to match the distance he wants the robot to traverse after turning (3c). The girl then programs the sequence in the computer as the boy begins to repeat his thinking (3d). The type of gestures reveals how learners built upon their basic moves in an embodied fashion to work more adeptly between their abstract and concrete thinking. Lakoff and Nunez (2000) explained how, as humans, we naturally draw on our basic bodily movements to better understand abstract concepts. From this perspective, the learners' gestures suggest that their thinking was highly embodied as they planned a solution path for the robot.

Figure 3. Gestures communicating basic moves combined into larger sequences of movement and thinking.

Tool 3: The map and the computer

The learners combined the visual block coding (i.e., computer program) and a small, hand-drawn map to serve as a tool for supporting their collaborative problem-solving. The map and computer together served as a physical representation of their thinking; they would visualize movements from the code itself and then attempt to act those movements out to determine if they would be effective. This is strong evidence of embodiment - learners were offloading cognition onto the map and computer, using the environment to mutually inform their cognition (Wilson, 2002). This is important because it shows how learners dealt with the abstract aspects of computer programming.

Figure 4 displays how the boy used the map (Figure 4a) and computer (4b) to plan a 90-degree turn. The boy explained: "That is where we take the turn (4c). And, that is delay [pointing to the screen, he finds the code that represents the delay] (4d)." The boy's gestures suggest that he has found two physical representations of his abstract thinking to better communicate with his partner. The learners are looking at both the codes on the screen and the location on the map to predict how the robot will move. They continued:

> B: To take the right turn, we need to set the time.
>
> G: For how many seconds?
>
> B: The half, point five,
>
> G: Point five... Sure [pointing to the screen, both learners look at the monitor and come to a mutual decision].

B: And now we need to set the delay.

This exchange suggests that the tools served as an affordance that helped them come to agreement. The physical representations of both the grid and the movement of the robot helped the learners visualize their thinking and determine whether they agreed with each other.
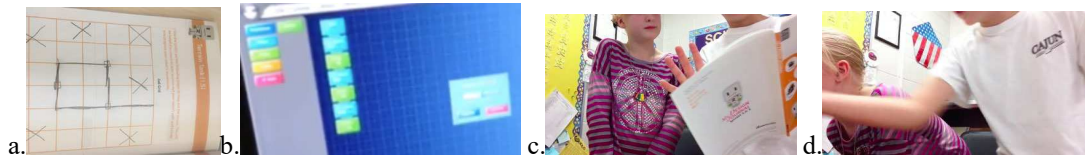

Figure 4. The map and computer together served as a physical representation of abstract thinking.

Tool 4: The robot at the grid

The robot also served as an important affordance that mediated perception and action. As the learners viewed the robot at the grid, they watched to see whether the robot's movements aligned with their overarching solution path for completing the task. To the extent that those movements did not, the learners returned to their other affordances (e.g., gestures; the map and computer) to debug their program or revise their intended goal in a collaborative fashion. This repeated itself until the task was successfully completed.

Figure 5 displays this process. At the grid, the learners see how the robot did not reach the intended destination (Figure 5a). The girl identified the problem: "We need to go really faster. Not alone faster but ... [pause, waiting for a response from her partner] (5b)." The boy then responds: "Let's make it the time [that 1`we used] before [waiting for an approval from the partner] (5c)." The girl then offers a guess: "Yeah, make the time...so point 3 more?" The boy then recognizes how they tried this speed setting previously, leading to a new solution in which they retrace their previous attempts at completing the overarching solution path.

Figure 5. The grid and the robot serve as a mediator between perception and action.

Conclusion and implications

This study presents a grounded theory of problem solving during robotics activity from an embodied perspective. The learners engaged in a process in which they were repeatedly evaluating whether their current thinking helped them achieve their overarching solution path. This process was emergent and reactive - sometimes they debugged their programming while other times they revisited their solution path. This dynamic process emphasizes the nature of cognition from the perspective of ecological psychology -- the learners set a goal, and information from the environment confirmed whether their actions helped achieve that goal. This is particularly apparent when looking across the learners' attempts at solving the overall task. Their second attempt took them in an entirely different direction than their first (see Figure 1). They then reacted to what emerged within the environment. Their third attempt is a continuation of their second rather than a re-creation of their first. In this way, their thinking shaped the environment while, at the same time, the environment shaped their thinking. This dynamic interplay between mind, body, and environment is at the heart of embodied cognition and typifies Gibson's (1979) notions of an affordance.

The tools identified in this study, then, illustrate how collaborative robotics activity is an embodied experience. Liben (2008) explained how, as humans, we engage in abstract thinking by manipulating external spatial representations both directly and symbolically. In this study, the robot at the grid provided direct access to the learners' problem solving. The learners they drew on their other tools to create symbolic access in the absence of direct access - they used gestures, the map, and the computer to communicate their thinking and create an effective solution.

These findings hold several implications for the embodiment of computational thinking during collaborative robotics activity in K-12 settings. To begin, learners may need a variety of tools to support their engagement in abstract thinking. Tools that provide symbolic access to their direct experiences with the robot can help them offload cognition into the environment during complex problem-solving. This can support collaborative activity. In this study, creating symbolic access helped the learners make their abstract thinking visible to each other. Tools such as maps, block programming, and basic movements helped them more effectively decompose a task, set goals, and create solutions that are mutually agreed upon. Others have similarly found that these tools can support robotics activity in the classroom (Harlow et al., 2018; Liben, 2012).

Additionally, this study offers insight into the way that collaborative robotics activity is an embodied phenomenon. While a great deal of attention has been spent on robotics and computer science, few if any studies view it from an embodied perspective. Viewing this activity as an embodied phenomenon opens a wealth of unexplored questions and potential for future research. For example, how can we design learning environments from an embodied perspective and be more responsive to learners' needs? How does the design of a robot affect how learners move between symbolic and direct access, and can we reduce the distance between these types of access? Moreover, what is gained by studying how we solve complex problems not as a linear, sequential process but rather as a coupling of perception and action in an emergent, complex setting? This study is an initial attempt at exploring these questions in the context of computer science and improving the design of computer-supported collaborative learning in today's schools.

References

Alibali, M. W. (2005). Gesture in spatial cognition: Expressing, communicating, and thinking about spatial information. *Spatial Cognition and Computation, 5*(4), 307-331.

Alibali, M. W., Nathan, M. J., Wolfgram, M. S., Church, R. B., Jacobs, S. A., Johnson Martinez, C., & Knuth, E. J. (2014). How teachers link ideas in mathematics instruction using speech and gesture: A corpus analysis. *Cognition and instruction, 32*(1), 65-100.

Birks, M., & Mills, J. (2011). Essentials of grounded theory. *Grounded theory: a practical guide*, 11-26.

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*: Sage.

Chemero, A. (2011). *Radical embodied cognitive science*: MIT press

Cuny, J., Snyder, L. & Wing, J.M.: Demystifying computational thinking for noncomputer scientists. Work in progress (2010)

Gibson, James J. (1977). "The Theory of Affordances." In Robert Shaw and John Bransford (eds.), *Perceiving, Acting, and Knowing*. Hillsdale, NJ: Lawrence Erlbaum Associates

Gibson, J. J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin Company..

Glaser, B., & Strauss, A. (1967). Grounded theory: The discovery of grounded theory. *Sociology the journal of the British sociological association, 12*, 27-49.

Grover, S., & Pea, R. (2013). Computational thinking in K–12: A review of the state of the field. *Educational researcher, 42*(1), 38-43.

Hammond, M. (2010). What is an affordance and can it help us understand the use of ICT in education? *Education and Information Technologies, 15*(3), 205-217.

Harlow, D. B., Dwyer, H. A., Hansen, A. K., Iveland, A. O., & Franklin, D. M. (2018). Ecological Design-Based Research for Computer Science Education: Affordances and Effectivities for Elementary School Students. *Cognition and instruction*, 1-23.

Hirose, N. (2011). Affordances, effectivities, and extension of the body. In W. Tschacher & C. Bergomi (Eds.), *The implications of embodiment: Cognition and communication.* (pp. 231–252). Charlottesville, VA: Imprint Academic.

Hirose, N. (2002). An ecological approach to embodiment and cognition. *Cognitive Systems Research, 3*(3), 289-299.

Ionescu, T., & Vasc, D. (2014). Embodied cognition: challenges for psychology and education. *Procedia-Social and Behavioral Sciences, 128*, 275-280.

Johnson, M. (2008). The meaning of the body. In *Developmental perspectives on embodiment and consciousness* (pp. 19-43). Psychology Press.

Johnson, C. W., & Parry, D. C. (2016). *Fostering social justice through qualitative inquiry: A methodological guide*: Routledge.

Kopcha, T. J., McGregor, J., Shin, S., Qian, Y., Choi, J., Hill, R., ... & Choi, I. (2017). Developing an integrative STEM curriculum for robotics education through Educational Design Research. *Journal of Formative Design in Learning, 1*(1), 31-44.

Israel, M., Pearson, J. N., Tapia, T., Wherfel, Q. M., & Reese, G. (2015). Supporting all learners in school-wide computational thinking: A cross-case qualitative analysis. *Computers & Education, 82*, 263-279.

Lakoff, G., & Núñez, R. E. (2000). Where mathematics comes from: How the embodied mind brings mathematics into being. *AMC, 10*, 12.

Liben, L. (2008). Representational development and the embodied mind's eye. *Body in mind, mind in body: Developmental perspectives on embodiment and consciousness*, 191-224.

Liben, L. S. (2012). Embodiment and children's understanding of the real and represented world *Developmental perspectives on embodiment and consciousness* (pp. 207-240): Psychology Press.

Linderoth, J. (2012). Why gamers don't learn more: An ecological approach to games as learning environments. *Journal of Gaming & Virtual Worlds, 4*(1), 45-62.

Lye, S. Y., & Koh, J. H. L. (2014). Review on teaching and learning of computational thinking through programming: What is next for K-12?. Computers in Human Behavior, 41, 51-61.

Malafouris, L. (2013). *How things shape the mind*: MIT Press.

Michaels, C. F., & Palatinus, Z. (2014). A ten commandments for ecological psychology. *Routledge handbook of embodied cognition*, 19-28.

Richardson, M. J., Shockley, K., Fajen, B. R., Riley, M. A., & Turvey, M. T. (2009). Ecological psychology: Six principles for an embodied–embedded approach to behavior. In *Handbook of Cognitive Science* (pp. 159-187).

Rietveld, E., & Kiverstein, J. (2014). A rich landscape of affordances. *Ecological Psychology, 26*(4), 325-352.

Rowlands, M. (2010). *The new science of the mind: From extended mind to embodied phenomenology*: MIT Press.

Sengupta, P., Kinnebrew, J. S., Basu, S., Biswas, G., & Clark, D. (2013). Integrating computational thinking with K-12 science education using agent-based computation: A theoretical framework. *Education and Information Technologies, 18*(2), 351-380.

Sullivan, A., & Bers, M. U. (2016). Robotics in the early childhood classroom: learning outcomes from an 8-week robotics curriculum in pre-kindergarten through second grade. *International Journal of Technology and Design Education, 26*(1), 3-20.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic bulletin & review, 9*(4), 625-636.

Wing, J. M. (2006). Computational thinking. *Communications of the ACM, 49*(3), 33-35

Yadav, A., Mayfield, C., Zhou, N., Hambrusch, S., & Korb, J. T. (2014). Computational thinking in elementary and secondary teacher education. ACM Transactions on Computing Education (TOCE), 14(1), 5.

Young, M. (2013). An ecological psychology of instructional design: Learning and thinking by perceiving–acting systems *Handbook of research on educational communications and technology* (pp. 180-188): Routledge.

Yuen, T., Stone, J., Davis, D., Gomez, A., Guillen, A., Tiger, E. P., & Boecking, M. (2015). A model of how children construct knowledge and understanding of engineering design within robotics focused contexts. *International Journal of Research Studies in Educational Technology, 5*(1).